Philosophy of Science (2022), **89**, 1124–1133
doi:10.1017/psa.2022.57

PSA PHILOSOPHY OF SCIENCE ASSOCIATION

PHILOSOPHY OF SCIENCE

SYMPOSIA PAPER

Measuring as a New Mode of Inquiry That Bridges Evolutionary Game Theory and Cancer Biology

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(Received 19 October 2021; revised 25 February 2022; accepted 02 May 2022; first published online 25 May 2022)

Abstract

We show that as game theory was transferred from mathematical oncology to experimental cancer biology, a new mode of inquiry was created. Modeling was replaced by measuring. The game measured by a game assay can serve as a bridge that allows knowledge to flow backward from target (cancer research) to source (game theory). Our finding suggests that the conformist and creative (Houkes and Zwart 2019) types of transfer need to be augmented. We conclude by introducing the expansive and transformative types to get a four-tier typology of knowledge transfer.

1. Introduction

Cancer is being increasingly recognized as an evolutionary disease, a malady due in part to the evolutionary dynamics of somatic cells within our bodies. Thus, understanding and treating cancer have required scientists to adopt ideas and develop new methods from evolutionary theory (for a philosophical discussion of cancer, see Plutynski 2018).

Mathematical oncology is a field in cancer research that focuses on using mathematical and computational modeling to study cancer. Evolutionary game-theoretic (EGT) modeling is prominent in mathematical oncology. It developed through knowledge transfer from theoretical evolutionary biology and economics.

In mathematical oncology, a typical EGT modeling paper begins by imagining—in the style of Weisberg's (2013, chap. 4) folk ontology—a scenario of two or more cells competing (see section 2). The theorist views the interacting cancer cells as having different behaviors, analyzes potential outcomes of the interaction, and summarizes them in terms of Darwinian fitness in a "payoff matrix." The mathematical oncologist then feeds this payoff matrix, as a parameter, to differential equations or computer simulations for further analyses (for a philosophical introduction to EGT analyses, see O'Connor 2020).

Starting by imagining interactions limits the EGT modeler to indirect representations (in the sense of Weisberg 2007). To address this limitation, Kaznatcheev et al. (2019) developed a "game assay" (see section 3). This game assay uses specifically designed experimental measurements to produce formal fitness functions and game payoff matrices from empirical cancer systems in the lab. For cancer biologists, the game assay offers a new method of studying cancer.

For philosophers, the game assay offers an opportunity to deepen our understanding of templates in knowledge transfer. Theoretical templates are "general representational devices occurring within a theory" that "can be successfully used to represent a variety of different phenomena within the domain of that theory" (Humphreys 2019, 114). Certain computational templates both allow scientists to represent a target system and facilitate quantitative manipulation (Houkes and Zwart 2019). Of the knowledge that is transferred between disciplines, templates are some of the most studied in the recent knowledge-transfer literature (Herfeld and Lisciandra 2019).

Following Weisberg's (2007) definition of modeling, we see that much of the recent literature is focused on the use of templates in the theoretical modeling mode of inquiry. This is unsurprising, given the origin of the concept of templates in Humphreys' (2002) analysis of computational models. Does this mean that templates cannot transform from theoretical to experimental modes? We give a resounding no. In section 4, we detail how the game assay created measurement as a nonmodeling mode of inquiry for game templates during their transfer from mathematical oncology to experimental cancer biology. We use this to show that templates do not have to respect the theoretical-versus-experimental boundary implicit in Humphreys (2019).

To understand how the game assay transformed its mode of inquiry, we need to elaborate the mapping from a formal template to its target domain. In section 5, we show how to decompose any template-to-target mapping into two parts: conceptual and concrete. In our case study of the transfer of games as templates from mathematical oncology to experimental cancer biology, it is the conceptual part of the map that was transformed. This allowed the change in the mode of inquiry. The malleability of the conceptual part of the mapping challenges Houkes and Zwart's (2019) claim of the inseparability of a template from its intensional interpretation.

A fundamental consequence of this new measuring mode of inquiry is that it allows for a reversal in the flow of knowledge from target to source. This allows us to explore the template-as-bridge metaphor in section 6.

We conclude in section 7 with a typology of knowledge transfer that augments Houkes and Zwart's (2019) conformist-versus-creative forms of transfer with our new dimension of change in the mode of inquiry. This new four-tier typology will allow philosophers of science to better study the application of mathematical constructs beyond theoretical modeling.

2. Reductive games: EGT modeling in mathematical oncology

EGT modeling in mathematical oncology is used like EGT in traditional theoretical biology. Game structure is interpreted from the perspective of individuals, except the charismatic macroscopic animals of zoology are replaced by the cancer cells of oncology (Hummert et al. 2014; Wölfl et al. 2021).

https://doi.org/10.1017/psa.2022.57 Published online by Cambridge University Press

As an example of the typical use of EGT modeling in mathematical oncology, consider the Go versus Grow game introduced by Basanta, Hatzikirou, and Deutsch (2008). One of the key steps in going from a benign tumor to a malignant cancer is metastasis, or the ability of a cancer to spread from one organ to another nonadjacent organ. According to Basanta et al. (2008), to achieve this, a cancer cell has to transition from a simple proliferative cell to a motile one. However, motility usually involves a cost to the cell. Basanta et al. (2008) represent this cost with the payoff matrix:

$$G^{\text{Go vs. Grow}} = \begin{pmatrix} \frac{b}{2} + \frac{1}{2}(b-c) & b-c \\ b & \frac{b}{2} \end{pmatrix}, \tag{1}$$

where the first row corresponds to the payoffs for a motile (or Go) cell, and the second row corresponds to the payoffs for a proliferative (or Grow) cell. As in traditional macroscopic EGT, the description of this game features two cells, with the strategy of the first cell determining the row of the matrix and the strategy of the second cell determining the column—the matrix element thus specified is the fitness effect on the first cell.

The particular kind of payoff matrix in equation (1) represents the intuition of how two cells interact as follows. When meeting at random in a resource spot, if both cells are motile, then one of them gets to stay in the resource spot and consume all the resources, and the other has to pay a cost c to move and find a new empty site with resources b. Which case happens to a particular cell is by chance, so they are weighted by $1/2$. On the other hand, if a motile cell meets a proliferate cell, then the motile cell will have to move for sure ($b - c$), but the proliferate cell can stay and eat all the resources (b). Finally, if two proliferate cells are in the same resource spot, then they simply share the resources, with $b/2$ for each.

Given that the kind of explanation just provided tends to reduce the game to the interactions of two (or a few) individuals, Kaznatcheev (2017, 2018) calls this sort of game a *reductive game*. Theorists in this tradition tend to explain population-scale phenomena by citing interactions between the individual units that make up that population. This interpretation takes players as individuals, strategies as behaviors of individuals, and the payoff as token fitness.

A salient feature of reductive games is their imaginary origins in a folk ontology (Weisberg 2013, chap. 4). For example, in the Go versus Grow game, we imagine two hypothetical cells that might meet and might move or not. Mathematical oncologists, or biologists in general, may give the imagined scenario more realism by, for instance, substituting the language of specific motility transitions for the strategies (e.g., the epithelial-mesenchymal transition). Indeed, the complexification of models with biological details is standard in biology more broadly, with the conviction that simple models "come to resemble the world more" as they get more complex (Dawkins 1976, 79). However, no amount of refining of the terms used to describe the interaction changes the imaginary nature of how a reductive game is conceived.

3. Effective games: Game assay in experimental cancer biology

To avoid this first step of imagining a reductive game, Kaznatcheev et al. (2019) develop an experimental procedure called the *game assay* to determine a game's

https://doi.org/10.1017/psa.2022.57 Published online by Cambridge University Press

payoff matrix in an empirical non–small-cell lung cancer (NSCLC) system in a glass plate (in vitro).

Kaznatcheev et al. (2019) start by identifying the strategies. In the clinic, NSCLC initially responds to the drug alectinib but eventually becomes resistant to this therapy. Thus, the authors grew a patient-derived drug-sensitive cell line (henceforth *parental*) and—through a drug-escalation protocol—created a drug-resistant cell line (henceforth *resistant*). Cells of the parental and resistant types were genetically modified to express a green and red fluorescent protein, respectively, so that they could be distinguished under the microscope. The resultant green and red fluorescent parental and resistant cells were taken as the two strategies to be studied.

With strategies identified, Kaznatcheev et al. (2019) considered four different environments in which to study the evolution of these two cell types. The cells were grown on glass plates with or without the presence of alectinib and with or without the presence of cancer-associated fibroblasts (CAFs; another cell type known to be important in NSCLC but that are not themselves cancer cells), resulting in four conditions: DMSO (no drug, no CAFs), DMSO + CAF, alectinib, and alectinib + CAF. These four global environmental conditions stand in for different situations that a patient with NSCLC encounters prior to and during treatment.

The actual experiments seeded the glass plates with different initial proportions of resistant versus parental cells and grew them for 5 days while filming the change in green versus red fluorescence under the microscope. The change in the number of red and green cells under the microscope over the 5-day period provides an estimate of the growth rate of the two types. Plotting this growth rate against the initial seeding proportion (p) of the two types produces a discrete approximation of a fitness function. By taking the line of best fit to these discrete points, Kaznatcheev et al. (2019) get a fitness function. The $p = 0$ and $p = 1$ intercepts of this fitness function then serve as the entries for the payoff matrix. Thus, Kaznatcheev et al. (2019) arrive at a measurement of the four payoff matrices corresponding to the four conditions:

$$G^{\text{DMSO}} = \begin{pmatrix} 2.5 & 2.4 \\ 4.0 & 2.7 \end{pmatrix} \; G^{\text{DMSO+CAF}} = \begin{pmatrix} 2.6 & 3.5 \\ 3.1 & 3.0 \end{pmatrix}$$

$$G^{\text{alectinib}} = \begin{pmatrix} -1.0 & -1.3 \\ 4.3 & 2.3 \end{pmatrix} \; G^{\text{alectinib+CAF}} = \begin{pmatrix} 0.5 & -0.4 \\ 3.8 & 2.4 \end{pmatrix}. \tag{2}$$

Note that here, unlike in the reductive games, the entries of the payoff matrix are in terms of type fitness. They do not represent an imagined interaction between two individual cells but instead are just a measurement of the magnitude of a type–type coupling. Kaznatcheev (2017, 2018) calls this sort of game an *effective game*. Here, the population-scale phenomenon is explained by citing interactions between the types that constitute the population, where the types are operationalized in terms of an experimental procedure (fluorescent area of green vs. red). This interpretation takes the player as a type-structured population, strategies as types, and the payoff as type fitness.

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4. Measurement as a new mode of inquiry

To understand the mode of inquiry, we follow Weisberg (2007) by considering both the procedures and the way in which scientists represent their phenomena of interest. Weisberg contends that scientists have to choose from a number of options, with one of them being modeling. Weisberg (2007) argues that when modeling, the modeler first imagines an abstract structure and then describes it using equations, pictures, graphs, and so forth for further analysis or refinement. Finally, if appropriate, the modeler "assesses the relationship between the model and the world" (Weisberg 2007, 209).

Weisberg calls these representations *model descriptions*. When the modeler intends to explain a real-world phenomenon by citing what she learns from analyzing the model description, her effort is said to be an *indirect* theoretical investigation of the real-world phenomenon. The indirectness in modeling is because a model description is a representation of the imagined structure, which in turn is a representation of a real-world situation.

As we saw in section 2, traditional EGT modelers follow this three-step process. Basanta et al. (2008) first imagine a scenario of competition between cells and summarize it as a game payoff matrix. Second, they study the behavior of this game structure by feeding a payoff matrix as a parameter into the replicator equation. In this sense, the equation and the payoff matrix determine the behavior of a game. Finally, they make a heuristic or qualitative comparison of the results of their analysis to their knowledge of cancer.

The game assay does not follow this process. In fact, Kaznatcheev et al. (2019) largely invert the process just described. In the game assay, the replicator equation is used to extract, not determine, the game structure from the behavior of the experimental system. The games extracted are an abstract summary of an experimental dynamic that was actually unfolding between the red (parental) and green (resistant) cell lines in the microscopic system in the lab. These games are thus a direct representation of what is happening in the glass plate.[1] Because the game assay produces a direct representation, Weisberg (2007) would not consider it as modeling—which he restricts to indirect representation.[2]

Traditional EGT modeling is a theoretical inquiry, whereas the game assay is a formal–experimental hybrid mode of inquiry. Given that the game assay takes a concrete object of an experiment as "input" and produces a theoretical object of a game as "output," we call this *the measurement mode of inquiry*. Thus, although the game structure is still representational in both EGT modeling and the game assay, the mode of inquiry to arrive at the representation has changed during the knowledge transfer from mathematical oncology to experimental cancer biology. Although both

[1] This "glass plate" is essential for the representation to be direct. If the system of interest is cancer in the human body rather than in a glass plate, then the game assay produces an indirect representation of the patient. This indirectness comes not from the theorists' imagination (i.e., folk ontology) but from the experimentalist's design. This indirectness is shared with all in vitro studies: cancer cells in vitro are not the same as cancer in the patient.

[2] The game assay is also not another description of a game structure. Although an "experiment contains a structure that can serve as a model" (Weisberg 2013, 25), the "formal" in a formal–experimental hybrid is primarily the replicator equation and does not include the game structure that the experiment produces.

https://doi.org/10.1017/psa.2022.57 Published online by Cambridge University Press

approaches can produce representations with empirical content, they do so by different modes of inquiry.

In regard to these modes of inquiry, Humphreys notes that "experimental knowledge, in the sense of knowing how to effectively carry out experiments or observations, does not seem to be a domain-transferable skill in the modern era" (2019, 118). Thus, Humphreys depicts a boundary between the theoretical mode of formal mathematical templates—where transfer between domains is rampant—and the experimental mode. Our case study, however, shows that this boundary is not defensible. Through the complex act of knowledge transfer, a formal template can switch from the theoretical-modeling mode to an experimental-measurement mode.

5. Expanding the template-to-target mapping

Humphreys (2019) defines formal templates as having no empirical content; all empirical content is gained from the mapping from the formal template to a target domain (what we will call the *template-to-target mapping*). In our case study, the formal template is the game, with its associated game-theoretic terms (*player*, *strategy*, *payoff*, etc.), and the target domain is cancer biology. Humphreys notes that "these mappings can be very complex and often consist of multiple embedded mappings" but does not elaborate or subdivide the mapping into different parts (2019, 116). Here we study the template-to-target mapping further by carefully subdividing it. In particular, the mapping between a formal template and the target domain can always be broken down into conceptual and concrete.

First, there is a conceptual mapping between the formal template and theoretical concepts in the target domain. For example, reductive games map the template's player to the domain concept of "individual," whereas an effective game instead maps the player to the domain concept of "type-structured population." At this point, the template with conceptual mapping still has no empirical content and cannot be false, but it can be wrong. The template terms and domain-concept terms must respect a shared "grammatical" structure. For example, in the formal template of games, players are "containers" of strategies, and so for reductive games in the target domain, individuals are "containers" of behaviors, and for effective games, type-structured populations are "containers" of types. If one instead mapped players to behaviors and strategies to individuals, then one would be wrong because behaviors do not "contain" individuals. But this wrongness is akin to a grammatical mistake rather than a falsehood.

Only in the second part of the mapping—the concrete mapping from concepts to objects in the target domain—can empirical content enter the template. Because this part of the mapping is fully within the target domain, its validity and truth value can be determined by the standards of that domain. Only at this point can a template be false—for example, if the template specifies that two variables should have a specific numerical relationship, but in the target domain, the objects those variables map to actually obtain a different numerical relationship.

This two-part mapping lets us make sense of how templates are interpreted. Humphreys notes "inseparability of the template and its interpretation" (2002, 10). Houkes and Zwart (2019) restrict this inseparability to just their notion of intensional interpretation (similar to our conceptual mapping) and not their notion of analytic

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interpretation (similar to our concrete mapping). For Houkes and Zwart (2019), the inseparability of the intensional interpretation and a template is essential for particular mathematical constructs to be more than "mere formalisms."

We find that this inseparability is true in the sense that a template cannot be used without an interpretation—the conceptual mapping is a part of any mapping between a formal template and the target domain. But our case study shows that this inseparability is false in another sense. During the transfer from EGT in mathematical oncology to EGT in experimental cancer biology, a game was separated from its reductive interpretation and replaced by the effective interpretation. Thus, we show that a template (i.e., a game) can be separated from its typical interpretation (i.e., player as individual, strategy as behavior, etc.). Knowing when and how to separate a template from its typical interpretation and which alternative interpretation to use can be central to successful knowledge transfer. Contrary to Houkes and Zwart's (2019) claim, wisely separating a template from intensional interpretation does not reduce the template to mere formalism but instead allows the template to transform in remarkable ways.

6. Templates as knowledge bridges

What we find most remarkable in the game-theoretic template's move from mathematical oncology to experimental cancer biology is its transformation from a transferred object to a bridging object. In everyday use, *transfer* is usually read as the movement of a fixed object from some source to some target. It does not imply modification of the transferred object or modification of source or target beyond the target now containing an object that it did not previously contain. But knowledge objects are not this static.

Some of these departures from the everyday use of the term *transfer* have already been noted by philosophers of science. For example, transferred objects might be modified through translation (Herfeld and Doehne 2019) or sanctioning (Bradley and Thébault 2019), and target domains might be modified through the creation of a landing zone (Price 2019). Although these insights perturb the transfer metaphor, they do not force us to replace it with something else.

Our case study, however, suggests that templates can act as bridges. First, the bridge metaphor can better represent how scientists employ a newly transferred template in their reasoning. Second, the transferred template can act as a way for knowledge to move "back" from target to source. This transfer is done not by passing another template but by moving "through" or "over" the representation set up by the template.

To see this, let us return to the four measured games in equation (2). All four of these payoff matrices are quantitatively different, and more importantly, they are of two qualitatively different kinds. The DMSO + CAF matrix is of a "LEADER" game kind (located in the upper-right quadrant of the game space in Figure 4b of Kaznatcheev et al. [2019]), whereas the other three are of a "DEADLOCK" game kind (all located in the bottom-right quadrant of the game space in Figure 4b of Kaznatcheev et al. [2019]). Two matrices are of qualitatively different kinds and correspond to different kinds of games if the relationship of inequalities between their payoff elements changes. DMSO, alectinib, and alectinib + CAF all have $G_{2,1} > G_{2,2} > G_{1,1} > G_{1,2}$, but DMSO + CAF has $G_{1,2} > G_{2,1} > G_{2,2} > G_{1,1}$. This leads to qualitatively different dynamics, with the former tending toward an end point with a single type (resistant)

https://doi.org/10.1017/psa.2022.57 Published online by Cambridge University Press

in the population, whereas the latter tends toward an end point of two types (parental and resistant) coexisting in the population.

None of these game structures had been previously imagined in the EGT modeling literature in mathematical oncology. But the occurrence of the LEADER game in the DMSO + CAF case, which Kaznatcheev et al. (2019) argue as corresponding to an untreated patient, is used as a potential explanation of why therapy resistance can emerge so easily (and why there is no "cost of resistance"). Let us look at the structure of this explanation, which follows three steps:

1. All games in the upper-right quadrant of the game space (see Figure 4b of Kaznatcheev et al. [2019]) have a mixed strategy equilibrium.
2. Mixed strategy equilibria correspond to the coexistence of the two types in the population.
3. The coexistence of sensitive and resistant types makes it easier for therapy resistance to emerge.

Whereas step 1 is a statement in the source domain, step 2 is a translation statement on the bridge, and step 3 is in the target domain. In this way, the template—or more specifically, the conceptual template-to-target mapping—acts as a way for the scientists to combine their knowledge of both the source and target domains and arrive at a new conclusion.

Note that contrary to the claim of Humphreys (2019)—and in support of the arguments by Bradley and Thébault (2019) and Lin (2022)—knowledge of both the target and source domains seems to be necessary for this explanation. In fact, without knowledge of the source domain, there is simply no reason to measure a game. One could simply describe the dynamics of the system without noting the connection to named games like LEADER or DEADLOCK. The reason that terminology from the source domain is used is so that knowledge from the source domain can have a direct bearing on the target.

It also allows knowledge from the target domain to affect the source. The game assay helps scientists focus on which of the possible game structures to study. Whereas EGT modelers choose games based on theoretical interest, the game assay can tell us which games tend to occur in empirical systems. This gives us knowledge of which games are interesting.

Finally, the shared representation between reductive and effective games allows scientists to jump between the measuring and modeling modes. For example, Farrokhian et al. (2020) use the game assay to measure the payoff matrix for parental versus resistant types interacting under different doses of the cancer drug gefitinib. They then use those measured games as starting points for traditional EGT modeling by taking the payoff matrices as parameters for subsequent replicator dynamics and even Lotka–Volterra models. The shared representation of games thus forms a bridge not just between mathematical oncology and experimental cancer biology but also between modeling and measuring.

7. Conclusion

Transformations in the mode of inquiry as one of the ways that templates can change during knowledge transfer suggest a two-dimensional, four-tier typology for

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transformative transfer. The first dimension roughly follows Houkes and Zwart's (2019) distinction between conformist and creative transfers. Crucial to Houkes and Zwart's differentiation is whether a modeler follows the typical structure of interpretation of the mathematical object being transferred, which in our case is the game structures. In terms of the way game structures are interpreted, any two episodes of EGT work may either be "in sync" or "diverge" from one another. The second dimension is concerned with the mode in which scientists use EGT to study their chosen subject. The modes can be matched—as in prior discussions of template transfer where both uses shared the modeling mode of inquiry—or mismatched. These two dimensions form a typology of four types of transfers: conformist, creative, expansive, and transformative.

Applying our typology, we find that EGT modeling in mathematical oncology can be matched and in sync with the standard EGT in evolutionary biology, but the work involving the game assay is mismatched and diverged from the two. Because Houkes and Zwart (2019) give examples of conformist and creative transfers, and the game assay serves as an example of a transformative transfer, it would be interesting for future work to look at the final type of transfer, expansive transfer.

Acknowledgments. We would like to thank the anonymous referee for their helpful comments. Artem Kaznatcheev was supported by a fellowship from the James S. McDonnell Foundation. Chia-Hua Lin was supported in part by National Science Foundation grant number 1922143 and in part by Taiwan's Ministry of Science and Technology grant number MOST 110-2811-H-007-514. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. Both authors contributed equally to this work.

References

Basanta, David, Haralambos Hatzikirou, and Andreas Deutsch. 2008. "Studying the Emergence of Invasiveness in Tumours Using Game Theory." *European Physical Journal B* 63 (3):393–97. https://doi.org/10.1140/epjb/e2008-00249-y.

Bradley, Seamus, and Karim P. Y. Thébault. 2019. "Models on the Move: Migration and Imperialism." *Studies in History and Philosophy of Science Part A* 77 (December):81–92. https://doi.org/10.1016/j.shpsa.2017.11.008.

Dawkins, Richard. 1976. *The Selfish Gene*. Oxford: Oxford University Press.

Farrokhian, Nathan, Jeff Maltas, Mina Dinh, Arda Durmaz, Patrick Ellsworth, Masahiro Hitomi, Erin McClure, Andriy Marusyk, Artem Kaznatcheev, and Jacob G. Scott. 2020. "Measuring Competitive Exclusion in Non-Small Cell Lung Cancer." *BioRxiv*. https://doi.org/10.1101/2020.09.18.303966.

Herfeld, Catherine, and Malte Doehne. 2019. "The Diffusion of Scientific Innovations: A Role Typology." *Studies in History and Philosophy of Science Part A* 77 (October):64–80. https://doi.org/10.1016/j.shpsa.2017.12.001.

Herfeld, Catherine, and Chiara Lisciandra. 2019. "Knowledge Transfer and Its Contexts." *Studies in History and Philosophy of Science Part A* 77 (October):1–10. https://doi.org/10.1016/j.shpsa.2019.06.002.

Houkes, Wybo, and Sjoerd D. Zwart. 2019. "Transfer and Templates in Scientific Modelling." *Studies in History and Philosophy of Science Part A* 77 (October):93–100. https://doi.org/10.1016/j.shpsa.2017.11.003.

Hummert, Sabine, Katrin Bohl, David Basanta, Andreas Deutsch, Sarah Werner, Günter Theißen, Anja Schroeter, and Stefan Schuster. 2014. "Evolutionary Game Theory: Cells as Players." *Molecular BioSystems* 10 (12):3044–65. https://doi.org/10.1039/c3mb70602h.

Humphreys, Paul. 2002. "Computational Models." *Philosophy of Science* 69 (S3):1–27. https://doi.org/10.1093/oxfordhb/9780199675111.013.026.

Humphreys, Paul. 2019. "Knowledge Transfer across Scientific Disciplines." *Studies in History and Philosophy of Science Part A* 77 (October):112–19. https://doi.org/10.1016/J.SHPSA.2017.11.001.

https://doi.org/10.1017/psa.2022.57 Published online by Cambridge University Press

Kaznatcheev, Artem. 2017. "Two Conceptions of Evolutionary Games: Reductive vs Effective." *BioRxiv*, 231993. https://doi.org/10.1101/231993.

Kaznatcheev, Artem. 2018. "Effective Games and the Confusion over Spatial Structure." *Proceedings of the National Academy of Sciences* 115 (8):E1709.

Kaznatcheev, Artem, Jeffrey Peacock, David Basanta, Andriy Marusyk, and Jacob G. Scott. 2019. "Fibroblasts and Alectinib Switch the Evolutionary Games Played by Non-Small Cell Lung Cancer." *Nature Ecology and Evolution* 3 (3):450–56. https://doi.org/10.1038/s41559-018-0768-z.

Lin, Chia-Hua. 2022. "Knowledge Transfer, Templates, and the Spillovers." *European Journal for Philosophy of Science* 12 (1):1–30.

O'Connor, Cailin. 2020. *Games in the Philosophy of Biology*. Cambridge: Cambridge University Press. https://doi.org/10.1017/9781108616737.

Plutynski, Anya. 2018. *Explaining Cancer: Finding Order in Disorder*. Oxford: Oxford University Press.

Price, Justin. 2019. "The Landing Zone—Ground for Model Transfer in Chemistry." *Studies in History and Philosophy of Science Part A* 77 (October):21–28. https://doi.org/10.1016/j.shpsa.2018.06.010.

Weisberg, Michael. 2007. "Who Is a Modeler?" *British Journal for the Philosophy of Science* 58 (2):207–33.

Weisberg, Michael. 2013. "Fictions and Folk Ontology." In *Simulation and Similarity: Using Models to Understand the World*, 46–73. Oxford: Oxford University Press. https://doi.org/DOI:10.1093/acprof:oso/9780199933662.003.0004.

Wölfl, Benjamin, Hedy te Rietmole, Monica Salvioli, Artem Kaznatcheev, Frank Thuijsman, Joel S. Brown, Boudewijn Burgering, and Kateřina Staňková. 2021. "The Contribution of Evolutionary Game Theory to Understanding and Treating Cancer." *Dynamic Games and Applications* 12 (2):313–42. https://doi.org/10.1007/s13235-021-00397-w.

Cite this article: Kaznatcheev, Artem and Chia-Hua Lin. 2022. "Measuring as a New Mode of Inquiry That Bridges Evolutionary Game Theory and Cancer Biology." *Philosophy of Science* 89 (5):1124–1133. https://doi.org/10.1017/psa.2022.57