DIAGRAMS, DIFFERENCE-MAKERS, AND BACKGROUND KNOWLEDGE

SIM-HUI TEE, Xiamen University Malaysia, Bandar Sunsuria, Malaysia

It is intriguing how scientific diagrams can facilitate scientific explanations. Philosophers argue that the difference-maker afforded in scientific diagrams can provide an explanation for the phenomenon of interest. I argue that difference-maker alone is insufficient to provide a well-informed scientific explanation. I articulate that the non-depicting relevant background knowledge has a significant role to play in diagrammatic explanations. The difference-makers play the solicitor role in soliciting the relevant explanatory resources from the relevant background knowledge of the depictum. An epistemic aggregation which regiments the relevant background knowledge may provide a well-informed scientific explanation of a depicted phenomenon.

1. Introduction

Diagrams are used extensively by biologists and biomedical practitioners to communicate ideas and facilitate research. Various types of diagrams, ranging from line plots to mechanism diagrams, serve the purpose of pedagogy and discovery. That diagrams play a significant role in biological sciences is evidenced by the fact that they are attributed with explanatory virtues (Perini 2005; Sheredos et al. 2013; Burnston et al. 2014; Love and Nathan 2015; Burnston 2016). A diagram which is explanatory facilitates scientific reasoning in the cutting-edge research, providing a perspicuous explanation for the relationship between variables of the phenomenon of interest. That diagrams as an explanatory device leads to an interesting question of how a diagram explains the target phenomenon.

There are two research directions in the attempt to answer this question. The first direction, which is irrelevant to this paper, probes into the cognitive capacity of humans in processing a diagram (see Larkin and Simon 1987; Zacks and Tversky 1999; Ainsworth and Loizou 2003; Bechtel 2017). Philosophers and cognitive scientists working in this direction aim at developing a theory to bridge the cognitive theory of

visual processing and the philosophical issues of scientific representation. The second direction, which is relevant here, aims at developing an account of explanatory relations according to which the visual representation of the data relation is brought out by the difference-makers in a diagram. The explanatory relations are "relations between variables that are relevant to explaining the phenomenon" (Abrahamsen and Bechtel 2015, 117). These variables are always characterized as quantitative data. The explanatory relations between variables are quantitative explanations of the phenomenon of interest (Burnston 2016; Scholl 2016).[1] Besides, the relations between variables are taken to exhibit the causal pattern of the data, from which the phenomenon of interest can be explained by looking at the causal contrast highlighted by the difference-makers of a diagram (Abrahamsen and Bechtel 2015; Scholl 2016). Difference-makers in a diagram are visual attributes that exhibit the causal or mechanistic difference between two (or more) variables in a diagram. They are often construed by philosophers to provide a quantitative explanation. This narrow interpretation of difference-makers does not explain how a difference-maker may be explanatory in a qualitative diagram. In this paper, I understand the term 'difference-maker': (1) in a broader sense, without limiting its usage to the interventionist framework; (2) to be able to provide a qualitative explanation in a scientific diagram. Difference-makers are visual attributes providing visual contrasts which may lead to causal or mechanistic explanation in a diagram.

However, scientific diagrams are not only explanatory in a quantitative way. There are diagrams, especially in biology, that are depicted qualitatively with various visual attributes such as shapes, color, icons, and drawings without any indication of quantity or number; yet this type of qualitative diagram can be explanatory (Hegarty et al. 1988). Besides, many diagrams bear both quantitative variables and qualitative visual attributes of the target phenomenon. Further, many diagrams do not depict specific quantities though the variables are visually indicated with symbols (e.g., symbol of gene).[2] In certain fields, qualitative metaphors are used in diagrams to symbolize the quantitative value of the phenomenon, such as Sewell Wright's use of topological contours to represent the adaptive value of gene combinations.[3] The qualitative attribute of an explanatory diagram can also be seen in many network diagrams that show either causal or

---

[1] Though Burnston (2016) discusses about the qualitative nature of causal graphs, he interprets explanatory relations in terms of quantitative relationship. He stresses the role of quantitative relationships between variables in explaining the phenomenon, as he writes "Even if the [qualitative] parts, operations, and organization of the mechanism are known, an explanation is often insufficient unless quantitative relationships are also represented" (p. 2).

[2] See: Goldbeter's diagram for the minimal cascade model for mitotic oscillations (1991, p. 9108, Fig. 1); Hardin, Hall, and Rosbash's diagram for the regulation of the level of *per* RNA by the PER protein feedback loop (1990, p. 539, Fig. 5); Ndii et al.'s diagram that depicts a flow chart of a dengue model (2016, p. 10, Fig. 1).

[3] See Ruse (1990) for a detailed discussion.

non-causal network relations between entities, properties, or events.[4] In biological diagrams that aim to depict the structure of an entity such as a macromolecule, the visual portrayal of structural similarity with the target entity is always the critical factor for this type of diagram to be explanatory—the qualitative visual attributes are emphasized over the quantitative attributes in this type of structure-depicting diagram.[5] Unfortunately, there is little attention from the philosopher on the qualitative explanatory relation of scientific diagrams, as the extant account on explanatory relation of scientific diagrams are quantitative. If one is to admit only quantitative explanatory relations, he will preclude many diagrams from being an explanation of the target phenomenon. This presents a grave problem especially to the new mechanist because parts and operations of a mechanism are always diagrammed in a qualitative way, or a mixture between quantitative variables and qualitative visual attributes. In this paper, I shall assume that the explanatory capa- city of a diagram lies in both quantitative and qualitative attributes. Because the explanatory relation depicted by difference-makers in a diagram is conventionally accounted for in a quantitative way, the extant account of difference-makers is insufficient to account for the qualitative diagram. I aim to develop an account of how difference-makers could be explanatory in qualitative diagrams.[6]

2. Difference-makers and explanation

Both quantitative and qualitative attributes of an explanatory relation matter in the explanation of the target phenomenon, despite the fact that most of the philosophers are inclined to define explanatory relations in terms of quantitative relationship. Implicitly focusing on the qualitative attributes of explanatory relations, Jones and Wolkenhauer (2012) articulate that a biological diagram explains by making information explicit via a localized grouping of the relevant difference-makers. They call such a diagrammatic representation a 'locality aid', which minimizes the user's search effort in extracting the required information for the purpose of inference and explanation. Jones and Wolkenhauer aim to show that biological diagrams could facilitate the construction of mathematical models and provide nomological explanations by grouping together the relevant information. It is far from clear that how such information grouping would provide the right sort of functional explanation as claimed by Jones

---

[4] See: Konopka et al.'s diagram that depicts the module eigengene overlaps in the brain regions of different species (2012, p. 605, Fig. 3).
[5] See: Burton and Hangartner's diagram for the structural interaction between an antibody and an epitope (2016, p. 647, Fig. 6); Patino et al.'s diagram for the structure of interleukin 5 and its receptor complexes (2011, p. 1866, Fig. 1); Morgan and Wolberger's diagram for the docking of the SAGA DUB module on ubiquitinated nucleosomes (2017, p. 77, Fig. 1).
[6] This paper does not concern about non-diagrammatic representation. Given that my arguments are canvassed around the issue of diagrammatic representation, I am not advancing an account of interpretation in general.

and Wolkenhauer, since, for instance, observing that DNAs and RNAs are grouped separately in a diagram convey nothing more than the categorical information about these two nucleic acids—no functional explanation of DNAs and RNAs can be obtained from such grouping. Diagrams as explanatory devices indeed providing us beyond categorical information about the phenomenon of interest. Jones and Wolkenhauer do not make explicit how the localized grouping of the relevant information contributes to the explanatory capacities of an explanatory relation between the diagrammatic components. A diagram does not provide functional explanation through grouping together the relevant information. Even when diagrams as locality aids do provide scientific explanation, it cannot provide a *well-informed* explanation of the target phenomenon—for mere grouping of difference-makers spatially does not provide an informative functional explanation. A *well-informed* diagrammatic explanation should provide sufficient amount of the relevant background information that is related to the depictum, allowing a diagram viewer to understand how and why the mechanism of interest works in the way as prescribed by the diagram. Though more often than not a diagram is not produced with every visual detail about the depicted mechanism, diagrams have the capacity to provide a well-informed explanation of the target phenomenon.

In a recent paper, Burnston (2016) argues from the practice of mammalian chronobiology that diagrams are explanatory in conveying the research finding. He articulates that an explanation of the target phenomenon is derived from the quantitative representation of the explanatory relations between variables. Multiple distinct types of diagrams are required in explaining a phenomenon, in such a way that "explanation is a cooperation between different ways of representing a system, not a competition between representations or models for explanatory primacy" (Burnston 2016, p. 11). Diagrams show visually various quantitative relationships between system components. However, it is ambiguous that in what way the qualitative visual attributes, such as colors, feature in the explanation of the phenomenon. Because explanatory relations that play the role of explaining are quantitative in Burnston's account, many qualitative visual attributes apparently do not have the explanatory power. However, Burnston implicitly grants the qualitative visual attributes an explanatory role, as he writes "Three examples of key ERs [explanatory relations] are shown below. The bar graphs are *color coded* to reflect the increasing amounts of siRNA [...]" (Burnston 2016, p. 6; my emphasis). It is mysterious that in what ways the qualitative visual attributes (e.g., colors) contribute to the explanation of the phenomenon (since Burnston interprets the explanatory power solely in terms of quantitative relations). The qualitative difference-makers (e.g., the different colors) in Burnston's account do not bear the explanatory capacity, yet they are apparently granted a role to explain.

Abrahamsen and Bechtel (2015) argue that inferences about the target phenomenon can be drawn from the contrasting patterns in the diagram. They hold that the information about the mouse's circadian rhythms is exhibited by different types of data patterns which are afforded by various types of diagrams. The contrasting patterns brought forth by difference-makers are visually discernible by tracing the qualitative visual attributes, such as the distribution of arrowheads (p. 127). By identifying the difference-makers of a diagram, one can delineate the phenomenon to be explained. Nonetheless, Abrahamsen and Bechtel do not provide an explicit account of how the difference-makers, which are qualitative visual attributes, are related to the explanatory relations, which are quantitative relationship by their definition. It is puzzling how mechanism diagrams, which "provide a visuospatial representation of the organized parts and operations of a mechanism" (p. 118), can construct and revise "a mechanistic explanation of the phenomenon" (p. 117) with the qualitative visual attributes such as drawings, icons, and arrowheads. Although Abrahamsen and Bechtel grant the explanatory role of an explanatory relation in mechanism diagrams, they provide no clues as to how the parts and operations of a mechanism, which are diagrammed qualitatively along with other qualitative visual attributes such as drawings and arrowheads, can reveal a quantitative relationship that is required in their account of explanatory relations.[7]

Scholl (2016) articulates a causal account of diagrammatic causal contrast which has the capacity to bring out an explanatory relation in the diagram. Working within an interventionist framework, Scholl aims to explicate how difference-makers highlight the causal contrast in diagrams.[8] Although Scholl states clearly that his work is related to answering one of the Abrahamsen and Bechtel's (2015) proposed functions of diagrams, viz., to identify explanatory relations "between variables that are relevant to explaining the phenomenon" (Abrahamsen and Bechtel 2015, p. 117), he understands explanatory relations as a causal relation. Following James Woodward, Scholl defines a causal relationship between variables C and E as "one where an intervention I on C results in a change in E in at least some background circumstances B" (2016, p. 78). Nonetheless, when applying Woodward's notion of causation to diagrammatic

---

[7] It is far from clear that how explanatory relations feature in the explanation in mechanism diagrams. In Abrahamsen and Bechtel's (2015) discussion on mechanism diagrams, and from their case study (in Fig. 6 of their paper), there is no explicit argument pertaining to the ways in which the explanatory relations, which are quantitative relations in their account, may contribute to the explanation in mechanism diagrams.

[8] Scholl's use of the notion of difference-makers is different from that of James Tabery (2009) and C. Kenneth Waters (2007), though all of them are using the notion under the framework of James Woodward's manipulability theory of causation. For Scholl, a difference-maker is a *diagram-based* difference-causal contrast that 'shows changes in an effect under particular interventions' (2016, p. 77). Tabery and Waters, on the other hand, use the term in the context of causal reasoning and the ontology of mechanisms.

explanation, Scholl reformulates it implicitly, as exhibited in the way in which he discusses his case studies, in such a way that: (1) the intervention on a variable in diagrams is not an external intervention (or force), rather, the intervention is represented using a visual attribute that 'causes' (in the diagram) visual differences in diagrams; (2) the difference between C and E in diagrams is the visual difference; (3) C and E in diagrams are difference-makers that bear the causal/explanatory relations; (4) a change on C and E is a *visually detectable* change of the qualitative or quantitative aspects of two variables in a diagram,[9] rather than the change of the variable's intrinsic value as defined by Woodward (2010).

One problem of Scholl's formulation and exposition of the diagrammatic explanation in the light of *visually* discernible causal relationship between variables is that such causal relationship *in* the diagram is not a causal relationship per se, viz., it is not the same type of the causal relationship as that held between variables C and E in the laboratory.[10] When scientists translate the causal relationship between C and E in the experimental setting to the diagram, the visually depicted variables C and E do not stand in the same causal relationship as they stand in the laboratory. Though the visually depicted C and E are the diagrammatic translation from the relevant variables in the experiment, it is false to claim that the visually depicted variable C causes the visually depicted variable E in the diagram. To avoid this, Scholl articulates that the causal relationship in a diagram is brought out by difference-makers. Many diagrams highlight the difference-makers by creating "appropriate [causal] contrasts to show changes in an effect under particular interventions" (p. 77). It is the difference-maker that makes the visually depicted variable C to 'cause' the visually depicted variable E in a diagram.

To sum up, philosophers generally agree that difference-makers play an explanatory role in scientific diagrams. The difference-makers are visual attributes that exhibit the causal or mechanistic difference between two (or more) variables in a diagram. These difference-makers can take the form of qualitative attributes (e.g., color, drawings, spatial arrangement) or quantitative attributes (e.g., quantitative data, figures). From the survey above, it is far from clear how difference-makers can provide a *well-informed* explanation in diagrams. A well-informed diagrammatic explanation should

---

[9] The *visually detectable* change of the *qualitative* aspect of two variables in a diagram can be seen in Scholl's discussion of his first case study, where he claims that the causal contrast is revealed by the presence/absence of visual marks produced in images of an electrophoresis gel. The *visually detectable* change of the *quantitative* aspect of two variables in a diagram can be seen in his discussion of the correlations between smoking and lung cancer, where he argues in such a way that the causal contrast is brought out by the reading of the bar graphs which are plotted with some indicative numbers.

[10] Although Scholl claims that causal contrasts are not obvious and may appear in many visual guises, the so-called 'causal' relationship between two variables in a diagram is a visually discernible relationship that is portrayed by a visual contrast.

provide sufficient amount of the relevant background information that is related to the depictum, allowing a diagram viewer to understand how and why the mechanism of interest works in the way as prescribed by the diagram. It is taken for granted by philosophers that difference-maker on its own can explain by providing some visual contrasts in the two-dimensional space of a diagram. How visual contrasts lead to diagrammatic explanation is left unaccounted for. In next section, I shall argue that the diagrammatic visual contrast alone, which is brought out by difference-makers, is insufficient to provide a *well-informed* scientific explanation of the target phenomenon. Epistemic aggregation is an essential mechanism that may facilitate *well-informed* explanation by regimenting the relevant background knowledge for the diagrammatic explanation of the phenomenon of interest.

Before I end this section, it is important to stress that I do not hold that diagrams alone, in the absence of background knowledge, do not explain; neither do I reject the standard approach to diagrams as non-explanatory. I argue that the existing accounts of difference-makers, which hold that the explanatory relation between the visual variables (in a diagram) is quantitative, may account for the explanation in a quantitative diagram but fail to provide *well-informed* scientific explanation in some diagrams, especially the qualitative ones. Lacking of *well-informed* explanation in a diagram does not mean that there is no explanation at all – such a diagram may still be explanatory but short for a comprehensive explanation. A comprehensive explanation (which I called "well-informed explanation") is possible provided that the relevant background knowledge about the diagram is epistemically aggregated into the diagram.

3. Difference-makers, background knowledge, and epistemic aggregation

Diagrams are often sketchy. Though some diagrams are subtly produced, the information provided in a diagram is always patchy due to the constraint of two-dimensional layout. A large amount of background information and relevant detail is omitted in a diagram. These background details are vital for the explanation of a sketchy depictum. Scientific diagrams can provide a well-informed explanation despite the constraint of its two-dimensional layout. A well-informed explanation provided by a diagram allows the viewer to understand the mechanism of interest in an unambiguous way, providing sufficient amount of information of the depictum in such a way that the viewer can understand how and why the mechanism of interest works in the way as prescribed in the diagram. To understand how and why a depicted mechanism works in a stipulated way require the establishment of an epistemic link from the depictum to the relevant background information of the mechanism of interest. For mechanists, "[t]o give a description of a mechanism for a phenomenon is to explain that phenomenon, i.e., to explain how it was produced" (Machamer et al. 2000, p. 3). To explain how a mechanism is produced always require more epistemic resources than the sketchy diagrammatic visual

attributes and variables. These depicta are associated with the relevant non-depicted background information of the mechanism of interest that can be mobilized as an explanatory resource by the diagrammatic visual attributes. As I have expounded in Section 2, difference-makers that visually portray the causal or mechanistic difference between two (or more) diagrammatic variables are unable to provide a *well-informed* explanation. To see this point clearly, let's consider two examples used by Scholl (2016). The first example uses a diagram which does not require much background knowledge in its interpretation, whereas the second example requires specific background knowledge in order to understand the diagram. I shall call the diagram in the first example a thin-background diagram, and the second example a thick-background diagram.
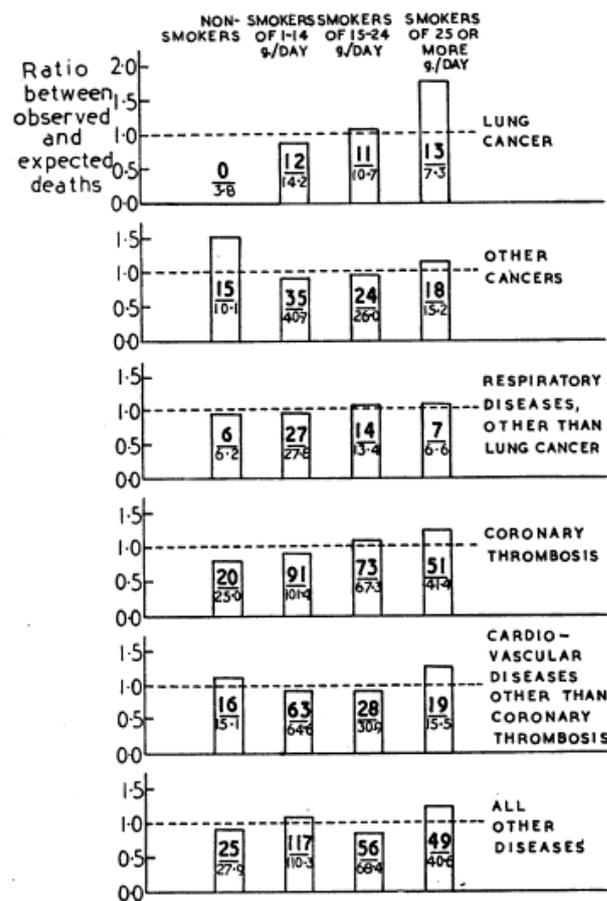

Fig 1.: Variation in mortality with tobacco consumption level (Adapted from Doll and Hill 1954, p. 1453).

830

Scholl's (2016) uses one of the diagrams in Doll and Hill's (1954) to argue for the role of visual contrasts in scientific diagrams. Doll and Hill's (1954) original diagram (shown here as Fig 1) displays the variation in mortality in relation to the tobacco consumption. The four bars on the horizontal axis of the graph and the ratio on the vertical axis are difference-makers that exhibit causal relationships between variables. Based on Doll and Hill's diagram, Scholl draws to our attention the difference-makers that highlight the causal difference between the variables of the levels of tobacco consumption and the variables of mortality. Scholl highlights two causal contrasts (which he claims they are not obvious to recognize) brought forth by the difference-makers, reproduced here as Fig 2.
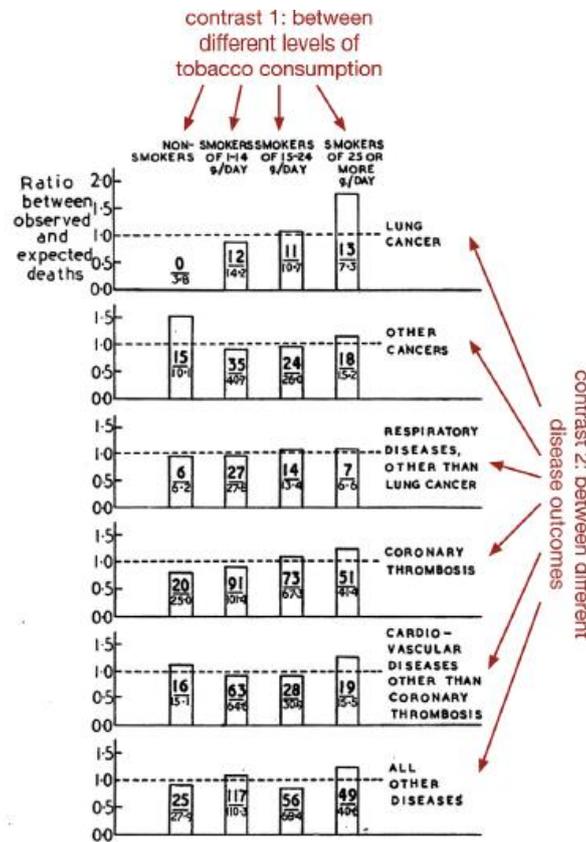

Fig 2.: Scholl's (2016, p. 83) reproduction of Doll and Hill's diagram (1954, p. 1453) with causal contrasts highlighted. It is an instance of a thin-background diagram.

Scholl holds that contrast 1 exhibits the causal relation between the increased tobacco consumption and the increased mortality due to lung cancer. It "concerns the difference in deaths from lung cancer between non-smokers, moderate smokers and heavy smokers" (Scholl 2016, p. 84). The contrast makes explicit the fact that smoking is a potential cause of death in lung cancer as the difference-maker in the diagram shows visually "the progression from a low number of deaths among non-smokers to an intermediate number in moderate smokers to a high number among heavy smokers" (p. 84). Though the difference-makers (four bars on the horizontal axis and the ratio on the vertical axis) provide the visual information about the different levels of tobacco consumption and the ratio between observed and expected deaths, the relationship between different variables requires the invocation of the relevant background knowledge to provide a *well-informed* explanation of the correlation between the increased levels of tobacco consumption and the increased deaths in lung cancer. Contrast 1 in the diagram serves the purpose of providing a *visual distinction* among different levels of tobacco consumption correlating to the mortality due to lung cancer; however, it does not provide a well-informed explanation about how and why such correlation is established in the way as illustrated—the *statistical implication of correlation* cannot be established on the basis of the visual contrasts.

One may argue that the answer to such a how- and why- question is apparent in the diagram. He may claim that the difference-makers in the diagram clearly show that the more one is to smoke, the higher mortality rate is to be resulted. I agree that one can understand such a correlation in contrast 1 which is brought out by the difference-makers, but I would like to point to the fact that such interpretation of the correlation between the different levels of tobacco consumption and the mortality rates is by no means a visual one. The difference-makers that bring forth the visual contrasts are engaged with the non-visual epistemic resources to bring about the interpretation of the correlation between the tobacco consumption levels and the mortality rates. The visual contrast on its own is unable to provide a *well-informed* explanation about the correlation between the tobacco consumption levels and the mortality rates. What is lacking in Scholl's and other mechanists' account is the solicitor role played by difference-makers in soliciting the epistemic resources from the relevant background knowledge of the depictum (in this example, the epistemic context of statistical correlation). The visual contrast on its own does not have the capacity to explain the correlation between smoking and lung cancer *if* the difference-makers fail to solicit the epistemic resources of statistical correlation. Statistical correlation as a statistical *notion* is not visual but conceptual. Though it is apt to say that a statistical notion can be hinted by visual attributes, its epistemic resources cannot be conveyed merely by visual means. By tracing visually

the depicted variables "from a low number of deaths among non-smokers to an intermediate number in moderate smokers to a high number among heavy smokers" (Scholl 2016, p. 84), one only sees the contrast of the visual pattern of bars plotted against the mortality rate. To recognize that this visual pattern reveals the fact that smoking is the cause of the lung cancer death, one needs an epistemic conception of correlation that supports the interpretation of the visual contrast in the diagram. However, one does not need to mobilize a rich stockpile of background knowledge about correlation from statistical science in order to understand the diagram in Fig 2, for this diagram is not entrenched in the context of highly specialized knowledge. Therefore, it is an instance of a thin-background diagram[11].

There is another type of diagram which is entrenched in the context of highly specialized knowledge, which I shall call it a thick-background diagram, reprinted below as Fig 3.

<hr>
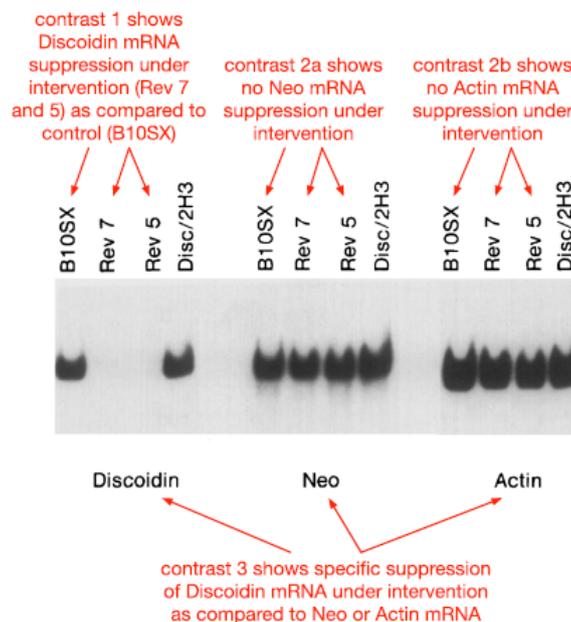
[11] A thin-background diagram does not require much specialized knowledge from the viewers. In general, even a layman can understand this type of scientific diagram. Having said that, certain amount of knowledge is needed to understand a thin-background diagram. A kid who does not have the required knowledge, for instance, will not understand a thin-background diagram such as Fig 2. In contrast, a thick-background diagram can only be understood by those who possess the required specialized knowledge.

Fig 3.: Expression of Discoidin I mRNA in transformants. Reprinted from Scholl (2016, p. 79). The original diagram was in Crowley et al. (1985, p. 635, Fig 3). It is an instance of a thick-background diagram.

Fig 3 shows a thick-background diagram that requires the viewer to possess the relevant specialized background knowledge to understand the depicted phenomenon. One will not 'see the meaning' in the difference-makers if she does not possess specific knowledge in the niche domains of vectors, RNA hybridization, gene expression, and so on. That is to say, without a rich set of the relevant background knowledge, the diagram appears to one just as some random blots of ink. What these blots of ink actually mean requires one to relate, using the visual clues and visual contrasts provided in the diagram, to the relevant background knowledge of various molecular players. In Fig 3, the difference-makers that exhibit the causal differences between the four interfering RNAs (B10SX, Rev 7, Rev 5, Disc/2H3) and the suppression of Discoidin I mRNA in comparison with the suppression of Neo and Actin are unable, *on its own*, to provide a *well-informed* explanation without invoking the relevant background knowledge that underlies the mechanism of interest. For instance, the relevant background knowledge needs to be solicited to explain the absence of the blots for Rev 7 and Rev 5 at the left panel of the diagram. Though difference-makers that highlight the absence of the blots do provide visual contrast (i.e., contrast 1 in Fig 3), they do not provide an explanation to account for the difference between the presence and the absence of the blots. The visual contrasts imply, by ways of synergistically soliciting the relevant background knowledge, that there is an inhibition of the Discoidin I mRNAs in cells transfected with the plasmid expressing anti-sense constructs. The scientific message brought out by this diagram has a more general connotation which requires a broader class of background knowledge in RNA transcription: an mRNA transcript can be regulated via the interference of small RNAs. Without the relevant background knowledge, one sees the visual contrast without understanding the message conveyed in the diagram.

In Fig 3, the visual contrast *on its own* does not have the capacity to explain the distribution of blots in the diagram. The same can be said of the thin-background diagram in Fig 2 above, that the visual contrast *on its own* is not self-explanatory about the *statistical notion* of the correlation between smoking and death in lung cancer. What is missing is an account that links visual contrasts in a diagram to the relevant background knowledge beyond the depictum. What I wish to argue is that the visual contrasts highlighted by difference-makers solicit the relevant background knowledge of the depictum for achieving a well-informed diagrammatic explanation. I formulate it as:

BK: Visual contrasts which are about a piece of fragmentary knowledge *k* solicit a class of knowledge *C* in which *k* resides. *C* consists of every piece of knowledge

(i.e., 'epistemic neighbors') related to k that is interacting epistemically with k to form a body of the relevant background knowledge K about some depicted mechanism M.

I acknowledge that visual contrasts are not about a body of systematic knowledge, and sometimes it is more appropriate to call a piece of fragmentary knowledge k to which a visual contrast refers as information or a fragment of fact. However, for the sake of simplicity I shall call the epistemic content to which visual contrasts refer as fragmentary knowledge. I also recognize the fact that it may not be plausible in all cases to delineate neatly the knowledge membership of each k, in view of the fact that k may belong to more than one class of knowledge. However, given the delimited representational context of a diagram, it is in principle plausible to assign k to one or more appropriate class of knowledge C. Each class of knowledge consists of a group of smaller pieces of constituent knowledge (I call them 'epistemic neighbors') that are related to each other and interacting with k to form a systematic body of background knowledge K.[12] Most of the philosophers assume that there is a direct route from visual contrasts about a fragmentary piece of knowledge k to a more systematic piece of background knowledge K, without taking into consideration the epistemic interactions between k and its epistemic neighbors (e.g., promoters, coding regions, and other molecular entities which are not shown in the diagram) that would jointly form K. Notably, k and its epistemic neighbors, which are all C's constituents, may interact in various ways to form a systematic body of background knowledge. The visual contrasts about k may not straightforwardly lead to one and only K, for there might exist more than one epistemic route such that the epistemic interactions between C's constituents may give rise to a set of systematic background knowledge K_n. The route between k and K_n is not visually depicted in the diagram. It appears mysterious that *how* a visual contrast about k can solicit a particular body of background knowledge K from a set of systematic background knowledge $K_1, K_2,..., K_n$ which may as well be equally plausible.[13]

As I have argued above that the visual contrast highlighted by difference-makers plays a solicitor role that solicits the relevant background knowledge to explain the depictum. How can the visual contrast about k solicit K_1 instead of K_2 from a set of background knowledge K_n be accounted for by the mechanism of an epistemic aggregation which groups the relevant epistemic neighbors in a specified way stipulated by the difference-makers? As argued above, different ways of interaction between k and

---

[12] I do not deny that C may give rise to more than one piece of systematic knowledge K, considering the fact that C's constituents may interact in varied ways.

[13] Most philosophers are resorting to cognitive processes to account for this issue, claiming that it is the cognitive process of scientists that selects a particular explanation (or background knowledge) about the depictum from a group of potential candidate explanations. My paper focuses only on the explanatory capacities of diagrams rather than on the role of cognitive processes in diagrammatic explanation.

its epistemic neighbors would lead to a different body of systematic background knowledge *K*. An epistemic aggregation functions to select, organize, and aggregate *k*'s epistemic neighbors based on the visual clues provided by the visual contrasts which are about *k*. The explanatory capacity of a diagram is explained by the way in which an epistemic aggregation regiments *k*'s epistemic neighbors which are residing in the relevant class of the background knowledge about the depictum.

BK thus formulated shows that what makes a scientific diagram explanatory is largely due to the solicited background knowledge of the depicted mechanism initiated by the visual contrast about the fragmentary knowledge *k*. The visual contrast about *k* on its own without the solicited relevant background knowledge cannot provide a *well-informed* explanation about the depicted mechanism.[14] It is not my task here to provide a detailed account of how an epistemic aggregation works in linking from the visual contrasts about the fragmentary knowledge *k* to the relevant background knowledge *K*.[15] My aim is simply to highlight the function of such a mechanism (i.e., epistemic aggregation) that picks up the visual clues from the visual contrasts, organizes and aggregates *k* and its epistemic neighbors in such a way that *K* is attained for a well-informed explanation of the depicted mechanism *M*. It suffices for my aim in this paper to demonstrate that the explanatory capacity of a diagram is derived from the relevant background knowledge about the depictum.[16]

To see the critical role of the epistemic aggregation in diagrammatic explanation, let's return to Fig 2 and Fig 3 above. Fig 2 is a thin-background diagram that illustrates the relationship between different levels of tobacco consumption and different disease outcomes. It is a thin-background diagram because one does not need to possess much specialized background knowledge (say, medical knowledge about the diseases) in order to understand the scientific message conveyed in the diagram. One has no difficulty to tell, at a glance, that the high level of tobacco consumption is the cause of death in lung cancer but is unlikely the cause of death in other diseases. This conclusion can be established easily by simply observing the visual patterns portrayed by the difference-makers (four bars on the horizontal axis and the ratio on the vertical axis) in the diagram that show visually "the progression from a low number of deaths among non-smokers to an intermediate number in moderate smokers to a high number among heavy smokers" (Scholl 2016, p. 84) in the category of lung cancer. One can also ob-

---

[14] I do not deny that visual contrasts about *k* can provide explanation about the depicted mechanism. What I am arguing is that without soliciting *K*, the explanation provided by *k* is fragmentary and may not be as comprehensive as that provided by *K*.

[15] This task requires a separate research paper.

[16] Diagrams provide information about the mechanisms for the sake of explaining phenomena produced by those mechanisms. Thanks for the comment of an anonymous referee.

serve easily that no similar patterns can be spotted in other category of diseases. Therefore, the diagram explains the fact that the level of tobacco consumption is correlated with the mortality due to lung cancer whereas having no effect on the mortality due to other diseases. This diagrammatic explanation qua scientific explanation, however, is not a well-informed *statistical explanation* of the correlation between the different levels of tobacco consumption and the mortality rate if one were to analyze the diagrammatic explanation based *merely* on the visual contrasts brought out by the difference-makers—because the visual contrast on its own does not afford the statistical notion of correlation. What a visual contrast affords is some visual patterns of the distribution of the visual attributes—how the bars are distributed across the diagram. The statistical notion of correlation is beyond the visual contrasts and the visual attributes; to put it in the context of *BK* discussed above, the statistical notion of correlation is the background knowledge K which is not visually depicted, therefore cannot be grasped through the visual contrasts portrayed in the diagram. An epistemic aggregation which groups the relevant epistemic neighbors in a specified way stipulated by the difference-makers can account for the well-informed statistical explanation of such correlation in Fig 2. The visual contrasts portrayed by the difference-makers solicit a class of statistical knowledge of correlation C in which the fragmentary knowledge k (e.g., the different levels of tobacco consumption) resides. An epistemic aggregation functions to select, organize, and aggregate k's epistemic neighbors in C based on the visual clues provided by the visual contrasts – how the different levels of tobacco consumption correlate with the mortality due to lung cancer and other diseases. The statistical correlation as a *well-informed* scientific explanation of the diagram is the product of an epistemic aggregation that conveys the relevant background knowledge about a statistical explanation of the effect of tobacco consumption. Though diagrammatic explanations can be provided by the visual contrasts brought out by the difference-makers, as demonstrated by mechanists in the literature on scientific diagrams (e.g., Abrahamsen and Bechtel 2015; Burnston 2016; Scholl 2016; Sheredos et al. 2013), the visual contrast on its own cannot provide a *well-informed* statistical (and scientific) explanation.

Similar thing about *BK* and the epistemic aggregation can be said of Fig 3, which is a thick-background diagram that requires specialized background knowledge from the viewer. A layman who does not possess the required knowledge of mRNA and the experimental protocols will not be able to understand the scientific message conveyed by the visual contrasts highlighted by the difference-makers. The visual contrast on its own does not afford the scientific explanation of the suppression of three mRNAs under distinct interventions—a layman who has no relevant scientific knowledge will see a rather random pattern of the distribution of blots. However, those who are well-

trained in the field can 'see' beyond the visual contrast to the scientific explanation regimented by the epistemic aggregation. Various epistemic neighbors (e.g., promoters, coding regions, etc.) are selected, organized, and aggregated by the mechanism of epistemic aggregation which functions to provide an epistemic link that will bridge up the visual contrasts of various RNA blots and the background knowledge of the intervention on mRNA translations.

It is now clear that the mechanism of an epistemic aggregation is essential to link up the visual contrast which is portrayed in the diagram to the *relevant* background knowledge which is beyond the visual attributes of the diagram. The epistemic aggregation is important in providing a *well-informed* explanation for the depictum by drawing the explanatory resources from the relevant background knowledge which is not visually portrayed in the diagram. What counts as the *relevant* background knowledge is determined by the epistemic neighbors of a piece of fragmentary knowledge *k* which is denoted by the visual contrast highlighted by the difference-makers. Epistemic neighbors are important because they constitute the relevant background knowledge that provides a well-informed scientific explanation for the target phenomenon depicted in the diagram. There are multiple ways in which the epistemic neighbors can interact to form a body of the relevant background knowledge that supports the scientific explanation of the depictum, and these multiple ways of interactions between epistemic neighbors are mobilized by the mechanism of an epistemic aggregation.[17]

4. Conclusion

Due to the two-dimensional space constraint of diagrams, it is always the case that diagrams are produced without much of the visual portrayal of the relevant background information. I argue that difference-maker on its own is insufficient to provide a well-informed scientific explanation of the depictum. I articulate that the explanatory resources of a scientific diagram lie in the relevant background knowledge which can be solicited by the visual contrast highlighted by the difference-maker. An epistemic aggregation functions to select, organize, and aggregate the relevant explanatory resources from the relevant class of background knowledge based on the visual clues

---

[17] Notably, diagrammatic representation can be found in chemistry where structural formulas are used to provide explanation in organic chemistry. Contrary to my examples of diagrammatic representation in biology, structural formulas are *formal* structures with two-dimensional arrangements of a fixed alphabet of signs consisting of letters, dots, and various types of lines (see Goodwin 2008). Thanks to an anonymous referee for pointing to the source). Many of the biological diagrams do not possess such kind of formal structures exhibited by structural formulas. The solicitation of the relevant explanatory resources from the relevant background knowledge is especially important in providing a well-informed explanation about the phenomena.

provided by the visual contrasts. The difference-makers play an important role in soliciting the relevant explanatory resources from the relevant background knowledge. The explanatory capacities of a diagram not only lie in the difference-makers but also in the relevant background knowledge which is not visually portrayed. The mechanist accounts of explanatory relations can be strengthened by my account because the explanatory capacity of a diagram can be accounted for by the explanatory resources provided by the relevant background knowledge of the depictum.

Bibliography

ABRAHAMSEN, A. and BECHTEL, W. (2015): Diagrams as tools for scientific reasoning. *Review of Philosophy and Psychology*, 6, 117 – 131. DOI: https://doi.org/10.1007/s13164-014-0215-2

AINSWORTH, S., LOIZOU, A. (2003): The effects of self-explaining when learning with text or diagrams. *Cognitive Science*, 27, 669 – 681. DOI: https://doi.org/10.1207/s15516709cog2704_5

BECHTEL, W. (2016): Using computational models to discover and understand mechanisms. *Studies in History and Philosophy of Science*, 56, 113 – 121. DOI: https://doi.org/10.1016/ j.shpsa.2015.10.004

BECHTEL, W. (2017): Diagrammatic reasoning. In: Magnani, L., Bertolotti, T. (Eds.): *Springer Handbook of Model-based Science* (605 – 618). Dordrecht: Springer.

BURNSTON, D. C. (2016): Data graphs and mechanistic explanation. *Studies in History and Philosophy of Biological and Biomedical Sciences*, 57, 1 – 12. DOI: https://doi.org/10.1016/ j.shpsc.2016.01.002

BURNSTON, D., SHEREDOS, B., ABRAHAMSEN, A., BECHTEL, W. (2014): Scientists' use of diagrams in developing mechanistic explanations: A case study from chronobiology. *Pragmatics & Cognition*, 22, 224 – 243. DOI: https://doi.org/10.1075/pc.22.2.04bur

BURTON, D., HANGARTNER, L. (2016): Broadly neutralizing antibodies to HIV and their role in vaccine design. *The Annual Review of Immunology*, 34, 635 – 659. DOI: https://doi.org/ 10.1146/annurev-immunol-041015-055515

DOLL, R., HILL, A.B. (1954): The mortality of doctors in relation to their smoking habits: A preliminary report. *British Medical Journal*, 1, 1451 – 1455. DOI: https://doi.org/10.1136/bmj.1.4877.1451

GOLDBETER, A. (1991): A minimal cascade model for the mitotic oscillator involving cyclin and cdc2 kinase. *Proceedings of the National Academy of Sciences of the United States of America*, 88 (20), 9107 – 9111. DOI: https://doi.org/10.1073/pnas.88.20.9107

GOODWIN, W. M. (2008): Structural formulas and explanation in organic chemistry. *Foundations of Chemistry*. 10, 117 – 127. DOI: https://doi.org/10.1007/s10698-007-9033-2

HARDIN, P., HALL, J., and ROSBASH, M. (1990): Feedback of the *Drosophila* period gene product on circadian cycling of its messenger RNA levels. *Nature*, 343, 536 – 540. DOI: https://doi.org/10.1038/343536a0

HEGARTY, M., JUST, M., MORRISON, I. (1988): Mental models of mechanical systems: Individual differences in qualitative and quantitative reasoning. *Cognitive Psychology*, 20, 191 – 236. DOI: https://doi.org/10.1016/0010-0285(88)90019-9

JONES, N., WOLKENHAUER, O. (2012): Diagrams as locality aids for explanation and model construction in cell biology. *Biology and Philosophy*, 27, 705 – 721. DOI: https://doi.org/ 10.1007/s10539-012-9311-9

KONOPKA, G., FRIEDRICH, T., DAVIS-TURAK, J., WINDEN, K., OLDHAM, M., GAO, F., CHEN, L., WANG, G-Z., LUO, R., PREUSS, T., GESCHWIND, D. (2012): Human-specific transcriptional networks in the brain. *Neuron*, 75, 601 – 617. DOI: https://doi.org/ 10.1016/ j.neuron.2012.05.034

LARKIN, J. H., SIMON, H. A. (1987): Why a diagram is (sometimes) worth ten thousand words. *Cognitive Sciencei*, 11, 65 – 99. DOI: https://doi.org/10.1111/j.1551-6708.1987.tb00863.x

LOVE, A., NATHAN, M. (2015): The idealization of causation in mechanistic explanation. *Philosophy of Science*, 82 (5), 761 – 774. DOI: https://doi.org/10.1086/683263

MACHAMER, P., DARDEN, L., CRAVER, C. F. (2000): Thinking about mechanisms. *Philosophy of Science*, 67 (1), 1 – 25. DOI: https://doi.org/10.1086/392759

MORGAN, M., WOLBERGER, C. (2017): Recognition of ubiquitinated nucleosomes. *Current Opinion in Structural Biology*, 42, 75 – 82. DOI: https://doi.org/10.1016/j.sbi.2016.11.01

NDII, M., ALLINGHAM, D., HICKSON, R., GLASS, K. (2016): The effect of *Wolbachia* on dengue outbreaks when dengue is repeatedly introduced. *Theoretical Population Biology*, 111, 9 – 15. DOI: https://doi.org/10.1016/ j.tpb.2016. 05.003

PATINO, E., KOTZSCH, A., SAREMBA, S., NICKEL, J., SCHMITZ, W., SEBALD, W., MUELLER, T. (2011): Structure analysis of the IL-5 ligand-receptor complex reveals a wrench-like architecture for IL-5Rα. *Structure*, 19, 1864 – 1875. DOI: https://doi.org/10.1016/ j.str.2011.08.015

PERINI, L. (2005): Explanation in two dimensions: diagrams and biological explanation. *Biology and Philosophy*, 20, 257 – 269. DOI: https://doi.org/10.1007/s10539-005-2562-y

RUSE, M. (1990). Are pictures really necessary? The case of Sewell Wright's "adaptive landscapes". *PSA: Proceedings of the Biennial Meeting of the Philosophy of Science Association*, 2, 63 – 77. DOI: https://doi.org/10.1086/psaprocbienmeetp.1990.2.193059

SCHOLL. R. (2016): Spot the difference: Causal contrasts in scientific diagrams. *Studies in History and Philosophy of Biological and Biomedical Sciences*, 60, 77 – 87. DOI: https://doi.org/10.1016/j.shpsc.2016.06.003

SHEREDOS, B., BURNSTON, D., ABRAHAMSEN, A., BECHTEL, W. (2013): Why do biologists use so many diagrams? *Philosophy of Science*, 80, 931 – 944. DOI: https://doi. org/10.1086/674047

TABERY, J. (2009): Difference mechanisms: explaining variation with mechanisms. *Biology and Philosophy*, 24, 645 – 664.

WATERS, C. K. (2007): Causes that make a difference. *The Journal of Philosophy*, 104 (11), 551 – 579.

WOODWARD, J. (2010): Causation in biology: stability, specificity, and the choice of levels of explanation. *Biology and Philosophy*, 25, 287 – 318.

ZACKS, J., TVERSKY, B. (1999): Bars and lines: A study of graphic communication. *Memory & Cognition*, 27 (6), 1073 – 1079.

_____

Sim-Hui Tee
Xiamen University Malaysia
EE and ICT
Jalan Sunsuria, Bandar Sunsuria
43900, Sepang
Malaysia
e-mail: simhui.tee@xmu.edu.my
ORCID ID: https://orcid.org/0000-0002-1922-7016