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Integrative Topologies: Customizable Models for Crossdisciplinary Knowledge Integration

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Abstract: Knowledge integration remains, paradoxically, both a key methodology and an elusive mystery in crossdisciplinary work such as interdisciplinary studies, team science, and transdisciplinary research. Many case studies have described compound events and iterations leading to remarkable integrative achievements. Even though a wealth of work on integration indicates that such achievements are common and desirable, there is no context-crossing approach to modeling how multiple integrations can connect to generate larger or more complex integrative results. There is thus an important need to develop an approach for unfolding integration that supports the full variety of integrative practices and theories. In the absence of such an approach, theorists and practitioners must either craft unique accounts for each case—which are difficult both to create and transfer—or reach general conclusions about what the smaller integrations have in common. This article draws upon and contributes to the philosophy of interdisciplinarity, proposing a new, structural approach to modeling connected integrations called *integrative topologies*. Each topology provides a model of connected integrations that can be customized for different situations instead of starting from scratch or abstracting away from intermediate integrations. First, the article develops simple rules for integrative pathways based on the input-process-output model of integration. Then, the weave, zipper, and chain topologies are introduced along with their hybrids. Next, the article illustrates how integrative topologies can make it easier to teach, plan, facilitate, describe, and evaluate complex combinations of expertise in crossdisciplinary work. The article concludes with areas for future philosophical research on knowledge integration.

Keywords: crossdisciplinary practice, interdisciplinary studies, knowledge integration, philosophy of interdisciplinarity, team science, transdisciplinary research

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1. Introduction

Complex combinations of expertise drive innovation and problem solving across the range of human activity. The synergy of diverse expertise is therefore a major concern in many fields, and they each frame it differently. To give a few examples, business scholars and leaders speak of "cross-functional teams" (Larson et al., 2022) and "organizational sense making" (Weick, 1995). Educators promote "cognitive flexibility" (Spiro, 2015) and "conceptual blending" (Fauconnier & Turner, 2002).[1] Cognitive scientists investigate "macrocognition" (Fiore et al., 2010). Here, I speak as a philosopher of crossdisciplinarity and frame the phenomenon as "knowledge integration." Paradigmatic examples of crossdisciplinary knowledge integration include using history, medicine, and statistics to track the maternal health legacy of redlining (Gao et al., 2023) or engineers working with neurobiologists to create a physical model of a neural network that can learn (Nersessian, 2022).

As a crossdisciplinarian, I join the many scholars and practitioners interested in various forms of knowledge integration, including interdisciplinarity and its cognates such as team science and transdisciplinary research (Darbellay, 2024; Hall et al., 2019; Klein, 2021; O'Rourke et al., 2024; Vienni-Baptista et al., 2023, 2024). I view knowledge integration broadly to include the socio-material factors involved in knowledge making. However, whether one includes these factors in a model or explanation of knowledge integration depends on one's purposes and the available information. This article develops an approach that can accommodate many decisions about, for example, whether data ontologies, experimental results, or dialogic exchanges are considered part of knowledge integration along with propositions, concepts, reasoning, and other "purely epistemic" content.

Integration remains, paradoxically, both a key methodology and an elusive mystery in crossdisciplinary work. Klein and Newell (1997, p. 404) call integration "the acid test of interdisciplinarity" and the United States National Science Foundation lists "deep integration" as a necessary condition for a type of crossdisciplinarity known as convergence research (National Science Foundation, n.d.). Others question the necessity of integration if it depends on commensurability or univocality but nevertheless uphold the centrality of interaction, a close cousin to integration (Choi & Richards, 2017; Holbrook, 2013; Lattuca, 2001; Organisation for Economic Cooperation and Development (OECD), 1972; Pohl et al., 2021).

While integration is important—perhaps essential—to crossdisciplinarity, it also resists clarity. Integration has been variously explained as a set of general principles (Klein, 2012), a stepwise process for individuals

1 For excellent reviews of educational theories that apply to "interdisciplinary learning," see Boix Mansilla (2017) and Klein (2021).

(Repko & Szostak, 2020), an iterative process for teams (Keestra et al., 2022), a multifaceted social process (Pohl et al., 2021), sudden insights (Pearce et al., 2022), reflective equilibrium (Boix Mansilla, 2017), information management (Zogheib, 2023), disciplinary heteroglossia (Nikitina, 2005), argumentation (Laursen, 2018), and metaphors such as blending and bridging (Boix Mansilla, 2010).

Despite this wealth of work on integration, there is no context-crossing approach to modeling how multiple integrations can connect causally or compositionally to generate larger integrative achievements, even though such achievements are common and desirable. Instead, theorists and practitioners must either craft unique accounts for each case—which are difficult both to create and transfer—or reach general conclusions about what the smaller integrations have in common.[2]

While they bring value in other ways, neither of these approaches accelerates practice or study of multi-stage integrations. In fact, the proliferation of case studies, on the one hand, and general models of integration, on the other, may hinder work on linked integrations by creating more somewhat-relevant options to consider. There is thus an important need to develop a transferable approach for unfolding integrations that supports the full variety of integrative practices and theories. This article proposes such an approach—*integrative topologies*—and illustrates how these topologies can make it easier to teach, plan, facilitate, describe, and evaluate complex combinations of expertise in crossdisciplinary work.

2. Single versus Multiple Integrations

A single instance of integration can be understood as an input-process-output (IPO) phenomenon (O'Rourke et al., 2016). On this model, two or more inputs are processed into fewer outputs without any of the inputs being removed. Instead, the process uses one or more integrative relations to induce dependencies between the inputs. Example integrative relations include sequencing (A comes before B), nesting (B is part of A), and analogy (A is like B). Integrative relations contrast with disintegrative and preservative relations (Laursen & O'Rourke, 2019). Disintegrative relations reduce dependence between inputs, dismantling them into more outputs; an example is distinction (A is not B). Preservative relations, like identity (A is A), leave inputs untouched.

While talk of an integrative "instance" may make it sound like these must be brief episodes, what counts as a single integration is in the eye of the

2 Nikitina (2005) exemplifies both approaches, narrating unique sequences of integrative moments in each of four interdisciplinary cases and summarizing them in an overall model of integration.

beholder. This is because the IPO model is a frame that allows one to identify something of interest—a unit of observation or analysis—and interests vary when describing integration. The original IPO model thus proposes that instances of integration can occur at various scales, levels of comprehensiveness, and levels of commensurability (O'Rourke et al., 2016).

For example, Laursen (2018) is interested in collaborative, interdisciplinary reasoning at the conversation scale. She therefore presents an integrative argument reconstructed from a Toolbox dialogue workshop as a single integrative episode, even though the conversation unfolded over several speaking turns. The inputs were perspectives on modeling from hydrology, engineering, sociology, and general research practice. The process was collaborative, interdisciplinary reasoning, a socio-material knowledge making activity. The output was the group's conclusion that "modeling in our project involves using statistics with empirical observations to operationalize the input-process-output concept" (Laursen, 2018, p. 89). Notice that Laursen does not specify the integrative relations at work in the process. This is partly because integrative relations are still undertheorized, partly because such relations were not part of Laursen's definition of reasoning, and partly because at larger scales that involve multiple steps or exchanges, it can be hard to identify the several relations that may have been involved in the extended process. Nevertheless, analyzing this conversation in terms of the IPO model revealed dynamics of collaborative, interdisciplinary reasoning that would have been hard to isolate if the process had been elided or conflated with inputs and outputs.

However helpful or interesting it is to model a single instance of integration, crossdisciplinary projects usually contain multiple instances. Keestra and colleagues (2022) find this to be true in their work with student teams, noting that integration occurs at multiple stages and is often iterative. Likewise, Boix Mansilla (2017) includes a role for "leveraging integrations" (plural) in her model of interdisciplinary learning. Case studies of integration are replete with multiple integrations that build toward larger achievements (e.g., Bechtel, 1993; Darden & Maull, 1977; Hoffmann et al., 2017; Nersessian, 2022; Nikitina, 2005; Plutynski, 2013; Poliseli & Caniglia, 2024; Repko et al., 2012). Pohl et al. (2021) summarize, "Integration can happen at manifold instances of a transdisciplinary research process" (p. 18). Indeed, Laursen's example above may have contained multiple instances, but the conceptual framework for analyzing these had not yet been developed. Even though multiple, manifold integrations are widely acknowledged to be common, there are no published models for how these may connect sequentially, in terms of either their causation or their composition.

The closest is from Andersen and Wagenknecht (2013), who developed three of Rossini and Porter's (1979) models for collaborative integration. The original models show integration occurring in at least two steps each but do not name the components or their relationships. The three newer models specify those, arguing that the models represent both social interaction and epistemic dependence. For example, instead of O→O, they specify $A_m \rightarrow B_n$ to indicate that person B, who knows *n*, comes to believe person A's assertion *m* during a conversation; that is, B becomes epistemically dependent upon A through a social interaction. While this brings more specificity to Rossini and Porter's models, it also loses some clarity about stages. In focusing on the types of relations between collaborators and what they know, Anderson and Wagenknecht leave the sequencing of intermediate outputs unspecified.

The IPO model provides foundational resources for filling these gaps in modeling connected integrations. By showing how outputs from one instance become inputs for another, we can clarify what is integrated (inputs), in what ways (processes and relations), and in what order (intermediate and final outputs).

3. Integrative Mechanisms and Pathways

On the IPO model, an integrative relation is the heart of the integrative process—the relation makes a connection among inputs—but other devices and arrangements may also be at work in the integrative process. Specifically, the process may involve an *integrative mechanism*. Generically defined, "integrative mechanisms are devices, systems, tools, or approaches that facilitate the combination of inputs into an integrated output" (McLeskey et al., 2022, p. 6). These mechanisms facilitate integration but may not become part of the integrated product.

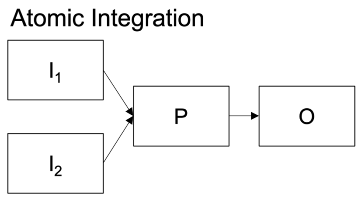
An example from forest economics illustrates an integrative mechanism. MacLeod and Nagatsu (2016) describe how economic and ecological models can be connected through a mathematical equation, creating a more robust economic model driven partly by an ecological model. Specifically, in the connecting equation, the solution from an ecological model is substituted for one of the economic variables (namely, volume of timber). Several metawork[3] arrangements facilitate this substitution, including that the economic and ecological models use similar spatiotemporal scales and that both models use a modular construction (Gerson, 2013). Special software powers the complex calculations. The replacement of one variable with another creates the integrative relation ("substitution") between two parts of the economic and ecological models, and the mathematical equation, metawork, software, and people are all part of the integrative mechanism that make the substitution work. Together, the mechanism and the integrative relation (plus lots of time and energy) constitute the socio-material integrative process MacLeod and Nagatsu call "model coupling." Other illustrative cases of integrative

3 Metawork is work that organizes other work (Gerson, 2013).

mechanisms could include argumentation mechanisms for interdisciplinary reasoning (Laursen, 2018), toolkitting (van der Tuin, 2021), model-based cognitive systems (Nersessian, 2022), and other "coordinative mechanisms of integration" (Gerson, 2013, p. 517).

The IPO model sets up an "atomic" instance of integration. That is, any instance of integration consists of exactly three parts: inputs, an integrative process, and at least one integrated output (Figure 1). When one integration feeds into another, they form *integrative pathways.*

Figure 1. An Atomic Instance of Integration, Consisting of at Least Two Inputs (I), One Integrative Process (P), and an Integrated Output (O)



McLeskey, O'Rourke, and Rinkus (2022, p. 6) defined an integrative pathway as "a series of changes whereby inputs are placed into integrative relations by integrative mechanisms in the production of integrated outputs." While helpful, this initial definition obscures some features of integrative pathways that are important for understanding how multiple integrations connect.

First, according to the tripartite nature of integration, a series of interdependent, integrative changes is accompanied by intermediate inputs and outputs. That is, multiple, related instances of integration each unfold with inputs, processes, and outputs. Tracking all three elements and proceeding stepwise through the pathway forces analysts and practitioners to get specific about what will be or has been done along the way to accomplish a complex integration. That is, observing or planning an IPO pathway as a whole entails specifying the steps as well, and both the parts and the whole are useful things to know.

Second, an integrative pathway, at least conceptually, need not include an integrative mechanism. Rather, the minimum logical operator in an integrative process is an integrative relation (O'Rourke et al., 2016). Integrative mechanisms are likely needed for all actual instances of integration because integration in the real world requires embodied knowers embedded in socio-material contexts (Pohl et al., 2021); concepts do not get integrated unless epistemic agents have bodies, materials, and contexts. However, such mechanisms are not strictly necessary for an IPO model of integration: A conceptual or highly schematic model of an integrative pathway need only include the integrative relation(s). When modeling or describing integration, the choices to specify the mechanism, the socio-material process, and/or the integrative relation depends on one's purposes for modeling integration and what information about the integration is available. Examples below illustrate these possibilities.

Third, and perhaps surprisingly, an integrative pathway may include disintegrative or preservative processes along with integrative processes. Components of a previously integrated output may only be available for further integration if they are first pulled apart from the whole. Such disintegration may reverse a previous integration, or it may simply divide it in a different way. Take, for instance, an integrative pathway for developing interdisciplinary insights that could be based on Repko and Szostak's (2020) process: First, the problem is *summarized* as a question (integrative process 1), then the question is *decomposed* into potentially relevant disciplines (disintegrative process 1), then these disciplines are *mapped* to show how they relate (integrative process 2), next, insights out of the relevant disciplines are *listed* (disintegrative process 2), and finally these insights are *integrated* (integrative process 3). What makes this an integrative pathway overall is that, at minimum, the last step is integrative.

A clarified definition is as follows: An *integrative pathway* is a series of changes whereby inputs are placed into relations in the production of intermediate outputs, culminating in an integrative relation that yields fewer outputs than inputs. The initial definition above by McLeskey and colleagues may better correspond to something like an *integrative trajectory*, a comprehensive direction of integration at the level of a project.

4. Integrative Topologies

Integrative pathways, like physical pathways, can have different shapes. The same shape can occur in different contexts, even when the contents or substrate of the pathways vary. Perhaps intuitively, on the IPO model the outputs from one instance of integration can become inputs for later instances of integration, forming integrative chains. But what other shapes are possible? How one or more integrative pathways are configured can be described as an *integrative topology*.

4.1. Mathematical Study of Topologies

In mathematics broadly, a topology is a structure that retains the relative positions of its components regardless of material, scale, rotation, or continuous deformation (*Topology*, 2024). Such structures are interesting not only in themselves—identifying them is not always easy—but also in the properties they have and the implications these properties have for how the object functions.

To dig into the implications of topology for integration, we first need to identify the broad category of topology that applies. Both continuous and segmented structures can have topologies. Continuous structures have no discrete parts; an example is a Mobius strip. Segmented structures, on the other hand, consist of discrete parts and their interconnections. The IPO view of integration lends itself to segmented topologies—specifically network topologies. Network topologies are described in the field of mathematics known as graph theory. Example topologies from graph theory illustrate the interesting nature of segmented topologies and the implications their properties have for how the structure functions.

For instance, a star or "hub-and-spoke" network topology is resource efficient yet fragile. When all nodes are connected through a single hub, it reduces the total number of connections needed to reach every node in the network from any other node. However, this structure could also delay or even prevent information flow if the hub goes offline.

In contrast, a mesh network is more resource intensive but resilient. In a mesh network, every node has the same number of connections as every other node. When these connections have the same strength, they space the nodes into a regular lattice and spread the resource load equally. With so many alternative paths between nodes, the network can still function if a node goes offline. However, it takes more resources to establish and maintain the additional connections over a star network.

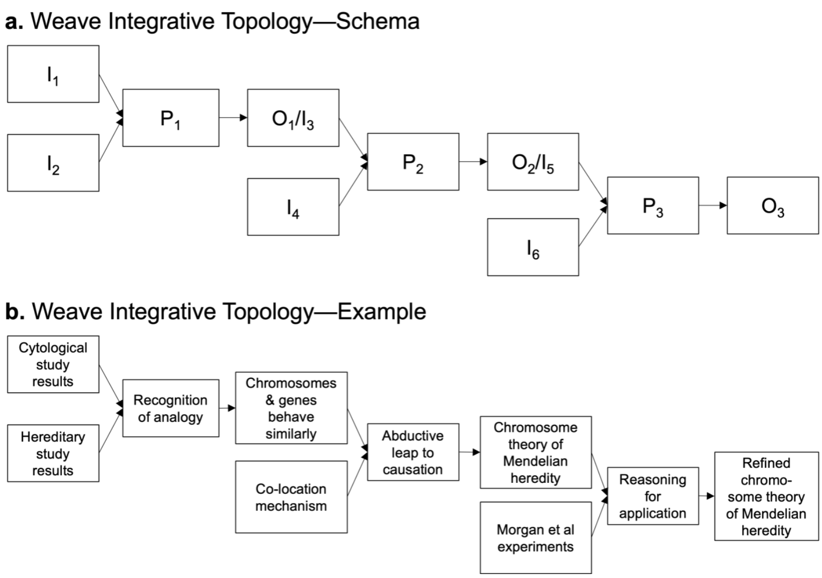
Likewise, an integrative topology is a structure, and its properties therefore influence the way the integration works overall. However, we cannot simply transfer the entire inventory of network topologies into the study and practice of integration because the IPO model places constraints on the types of nodes available and how they can be connected: With each integration modeled as an ordered tuple of inputs, processes, and outputs, multiple integrations can only connect in certain kinds of graph or network topologies. For example, the star and mesh networks are not possible for integrations. A star network has only one kind of connection (a spoke), while integrations require two kinds (inputs-to-process and process-to-outputs). A mesh network requires every node to be connected to the same number of nodes. However, IPO sets have more inputs than outputs, and these cannot connect with each other except through a process; inputs, for example, cannot connect with neighboring inputs. Next, I introduce three basic integrative topologies and several combinations of them that conform to the constraints of the IPO model of integration.

4.2. Integrative Weaves

The first topology I will introduce is an integrative weave. In a weave, each output becomes a subsequent input, *and* a new input, previously not present in the integration, is added (Figure 2a). In a basic weave, only one new input is added at time; more complex weaves may add more. As the weave extends it contains more and more inputs in a single output; or, put another way, more and more inputs influence the production of the output.[4] This makes the weave an apt structure for unification-style projects in which all inputs are moving towards a single output, such as a theoretical framework. Relative to zippers, which I discuss next, weaves can be easier to plan, execute, and understand because they may integrate only one additional input at a time. A supervisor might advise their student to use this topology as a template for creating an integrated theoretical framework as they learn how to do crossdisciplinary research. I will return later to the use of topologies as a teaching tool, but first I will provide an example of a completed weave.

One of the classic "interfield theories" described by Darden and Maull (1977) was developed through a weave topology (Figure 2b). Although much came before, here I pick up the story when scientists noticed that results from cytological studies about chromosomes were remarkably like results from hereditary studies about genes. In IPO terms, they established the integrative relation of analogy between inputs (experimental results) from two distinct disciplines. Then, scientists postulated that these observations were caused by a previously unrecognized mechanism: co-location of the genes and chromosomes. This yielded the interfield chromosome theory of Mendelian heredity,

Figure 2. The Basic Weave Topology. (a) Generic Schema, (b) Example with content from Darden & Maull (1977)



4 I remain neutral in this article about whether the "series of changes" in an integrative pathway is causal, compositional, or both.

which states that “genes are in or on the chromosomes” (Darden & Maull, 1977, p. 52). Finally, this theory was integrated with further empirical results when applying the theory to those results. Darden and Maull do not detail this application work but reference two books and a key article by Morgan and colleagues (Morgan, 1911, 1926; Morgan et al., 1915). These publications contain a complex set of arguments, and it is beyond the scope of this article to analyze their various logics and the integrative relations they employed. However, ultimately, their reasoning resulted in a refined interfield theory asserting that genes are in the chromosomes.

Notice that in terms of scientific practice, the inputs changed at every step: At first, the inputs were two sets of results, and then results and a mechanistic explanation, and finally a theory and later results. This was an integrative pathway. However, if we tried to tell an IPO story in terms of the topics the scientists were studying, the inputs would have stayed the same along the way—genes and chromosomes—while the outputs would have changed. With each phase of research, scientists revised their understanding of the relationship between genes and chromosomes, from *similarity*, to *co-located*, to *part-whole*. This series of changes in the gene-chromosome relation, having the same inputs but a different output each time, was not an integrative pathway. The intermediate outputs did not become subsequent inputs. Rather, the integrative pathway of doing the science revised understanding of the topic along the way. This is an example of integrative thinking about an integrated thing. While the integrated nature of the world is often given as a reason to do crossdisciplinary work (e.g., Newell, 2001), this example topology shows that the thinking process does not necessarily follow the same shape as the topic.

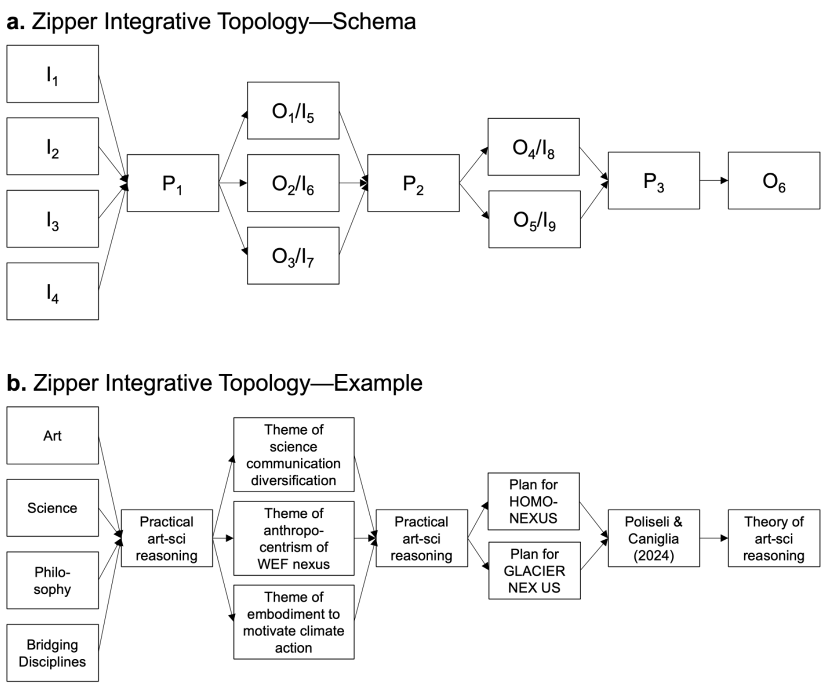
4.3. Integrative Zippers

Like the weave, the zipper topology can also aim for a single output. However, instead of adding inputs along the way, a zipper starts with all inputs and gradually integrates them, successively reducing the number of outputs through a series of integrations until the final output(s) contain or are influenced by all the preceding inputs (Figure 3a). This is also a unification project but can be harder to do or understand than a weave because there are more inputs to track at each step.

An example of the zipper topology in action can be found in the art-science project described by Poliseli and Caniglia (2024). The project’s overall goal was to create art-science interventions that would motivate viewers of the art to act against climate change. As Figure 3b shows, their integrative pathway began with researcher-participants bringing their perspectives from art, science, philosophy, and bridging disciplines (art history and sustainability science). Through practical reasoning across nine workshops, they integrated their insights into three themes: (1) the need to diversify science communication, (2) the anthropocentrism of the "water-energy-food (WEF) nexus," and (3) the value of embodiment for motivating climate action. Through more practical reasoning, these three themes became criteria for guiding the design of two art-science interventions (namely, HOMONEXUS and GLACIER NEX US). Finally, the authors analyzed the results and process from both interventions in their article, generating a coherent theory of interdisciplinary reasoning in art-science teams. Note that based on the information we have, each integrative step involved complex, socio-material integrative processes and mechanisms while the integrative relations are left implicit.

This summary and Figure 3b capture the process after it was done. However, Poliseli and Caniglia (2024) describe how the key themes and design of the interventions unfolded at different times. An animated version of Figure 4 might show parts of the pathway forming little by little. For example, part of the theme about embodiment first emerged as the importance of slowing down, which guided HOMONEXUS directly. But later, this theme evolved to include the importance of empathizing, and so personifying a glacier became a key feature of GLACIER NEX US. That is, the overall integrative pathway of

Figure 3. The Basic Zipper Topology. (a) Generic Schema, (b) Example with content from Poliseli & Caniglia (2024)



this project consisted of many smaller pathways and partial pathways. This example shows that while integrative topologies portray stepwise progress, they do not enforce algorithmic or linear activity. Poliseli and Caniglia (2024) do not use the IPO model or "integrative pathways" in describing the project, instead presenting "inter- and transdisciplinary reasoning trajectories." However, translating their account into a topological format is instructive, revealing that a zipper of integration facilitated this iterative, multivocal, art-science collaboration.

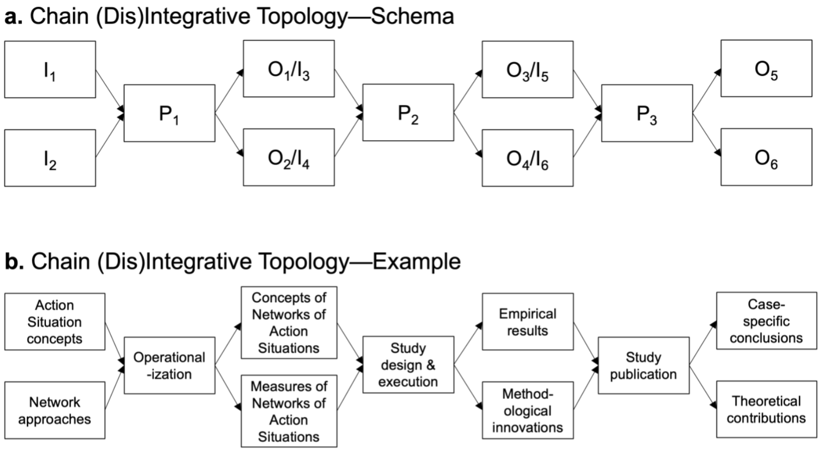
4.4. (Dis)Integrative Chains

I mentioned earlier that integrative chains may seem intuitively obvious, since integrated outputs can become inputs for later integrations. But if we dig into what this means, there is surprising complexity. To create a chain purely from outputs of the previous integration requires every process along the way to produce at least two outputs. This is because it is not possible to integrate an indivisible, lone input resulting from a previous integration; such an output would terminate the chain. In turn, each time two or more outputs are required, the same number of inputs are required. This is because if there were more inputs than outputs at a given step, that would be a zipper. In short, a chain preserves the number of inputs and repeatedly remixes them into different outputs (Figure 4a).

The nature of these "remixing" processes brings hidden complexity, for these cannot simply integrate inputs straight away; that would reduce the number of outputs. Neither can the process pass inputs straight through, unchanged, for that would be preservation not integration. Rather, in each step of a chain there must be some initial disintegration of the inputs and then reintegration into a new set of outputs. This reveals chains to be far from simple because they inherently involve other relations besides integrative relations. More properly they might be labeled (dis)integrative, remixing, or even transformative chains.

While the chain brings complexity, in practice chains may be common, especially for large or extended integrations that involve many actors. However, at large scales, it is difficult to track the specific relations involved in each process. For example, Kimmich et al. (2023) document an emerging interdisciplinary field called Networks of Action Situations (NASs). The emergence of this field can be modeled as a (dis)integrative chain (Figure 4b). Kimmich and colleagues focus on empirical NAS studies. In such studies, researchers first take concepts of Action Situations from one set of theoretical resources and network approaches from another set. Researchers then *operationalize* empirical questions from these conceptual resources—a complex process that is both integrative and disintegrative—creating concepts and measures of NASs. Researchers then use these concepts and measures to *design and execute* their studies, which involves both pulling apart and putting together concepts

Figure 4. The Basic Chain Topology. (a) Generic Schema, (b) Example with content from Kimmich et al. (2023)



and measures in various configurations. This produces both empirical results and methodological innovations. Finally, through *publication*, which involves both dividing a study into parts and synthesizing some of those parts, these studies result in case-specific conclusions and theoretical contributions that develop the field. Each phase of this work (operationalization, study design and execution, and publication) remixes inputs into new outputs, ultimately making connections between different theoretical traditions and empirical and methodological domains to form a new field.

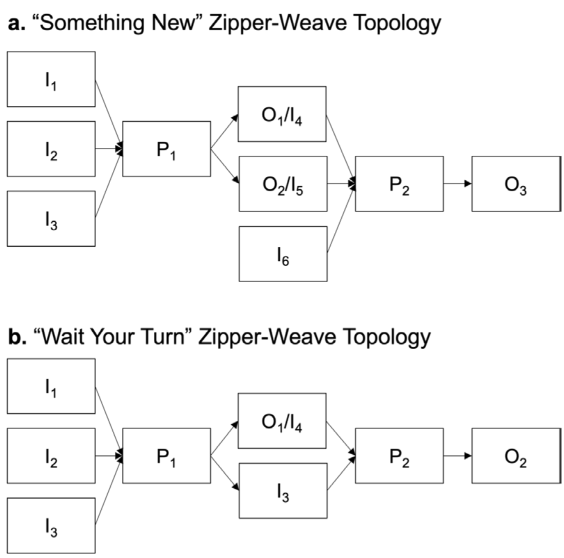
As with Poliseli and Caneglia (2024), and so many other accounts of integration, Kimmich and colleagues (2023) do not provide information about the specific (dis)integrative relations at the heart of these processes. However, by comparing the numbers and natures of inputs and outputs from these processes, such relations are inferred to be present. Deeper ethnographic and archival research might reveal disintegrative relations such as *decomposing* a collection of measures into its parts and integrative relations such as *subsuming* some results in a more general theory.

This topology, and this example, may feel like they stretch the boundaries of what counts as an integrative topology. Indeed, they do. But rather than cast doubts upon integrative topologies, these stretch cases in fact brighten the boundaries by showing how far integrative topologies can and cannot go. The (dis)integrative chain shows that a purely integrative chain is never possible. This discovery is not only interesting but useful: It legitimizes a role for disintegration even within an integrative project. The example shows that it is possible to use a topology to describe large integrations, such as those at the scale of entire disciplines. However, the example also shows there is a tradeoff when analyzing integration at such a large scale: It becomes difficult to track the integrative and disintegrative relations in operation. The fact that the topologies start to get blurry at these boundary cases indicates not that the topologies are suspect but rather that crossdisciplinary practice is not as purely integrative as we are sometimes led to believe (Gerson, 2013; Misra et al., 2024; O'Malley, 2013); that analysts might gain more clarity about integration by observing it at small scales (Nersessian, 2022; O'Rourke et al., 2021); and that without careful tracking of integrative relations, accounts of integration are more open to interpretation and may function more like boundary objects than proofs (Klein, 2021; Star, 2010).

4.5. Hybrid Topologies

Weaves, zippers, and chains can hybridize. For example, a zipper-weave could add a new input after a couple of zipper integrations (Figure 5a). Another type of zipper-weave may gradually incorporate inputs that have been present from the beginning but preserved until the time is right to integrate them (Figure 5b), a kind of partial integration (Gerson, 2013; Repko, 2012). In such cases, the inputs that are waiting to be integrated may be involved in the integrative process, perhaps as part of the integrative mechanism, but they are not incorporated into the output at first.[5]

Figure 5. Zipper-Weave Hybrid Topologies, Each Manifested in a Single Pathway. (a) "Something New" Zipper-Weave, (b) "Wait Your Turn" Zipper-Weave



5 In some cases, the time is never right to integrate certain inputs, and they are carried along throughout.

4.6. Stacked Topologies

Not only can pathways hybridize, or include elements of different topologies, but they can also stack. That is, two or more integrative pathways, each including multiple instances of integration, can combine to form a larger one. This may describe model coupling, for example, where each model integrates in multiple stages and the two models themselves are also integrated. Thus, an integrative topology could describe a single integrative pathway or more than one. Figures 2 through 5 show topologies manifested in a single pathway at a time. Figures 6 and 7 show stacked topologies, each containing two pathways for illustration. These include a double weave topology, two double zipper topologies, and a double weave-zipper topology.

In summary, an integrative topology is the shape of one or more integrative pathway(s), each of which can be modeled in terms of integrative inputs, processes, and outputs. Figures 2 through 7 show just a few examples of the many topologies waiting to be articulated. Now, let's explore how the concept of integrative topologies might be useful in crossdisciplinary practice.

Figure 6. Stacked Weave and Weave-Zipper Topologies, Each Consisting of Two Pathways. Cross-Hatched Components are Part of Both Pathways. (a) Double Weave Topology, and (b) Double Weave (White)-Zipper (Gray) Topology

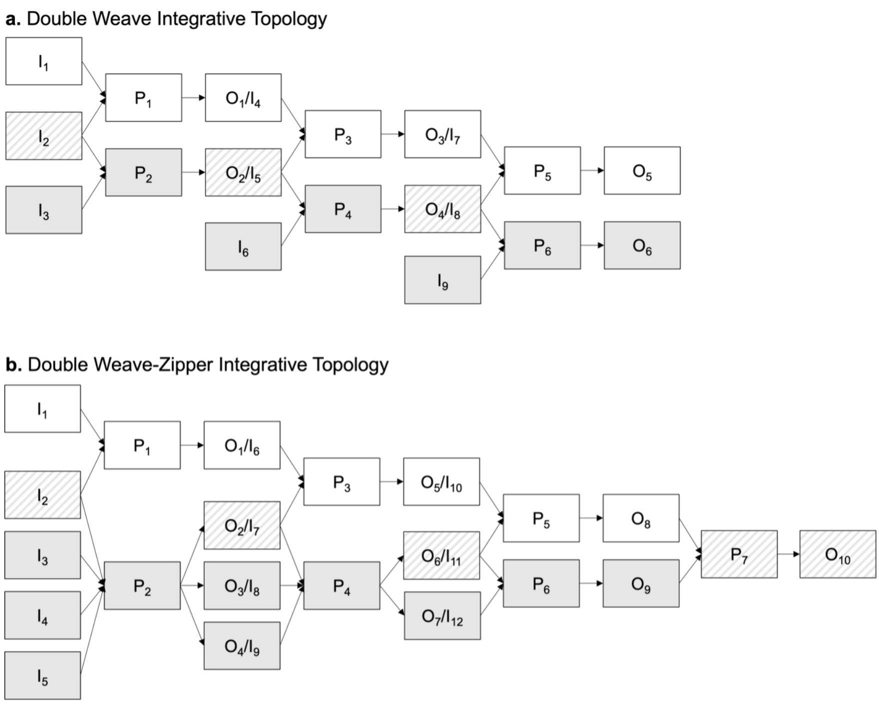
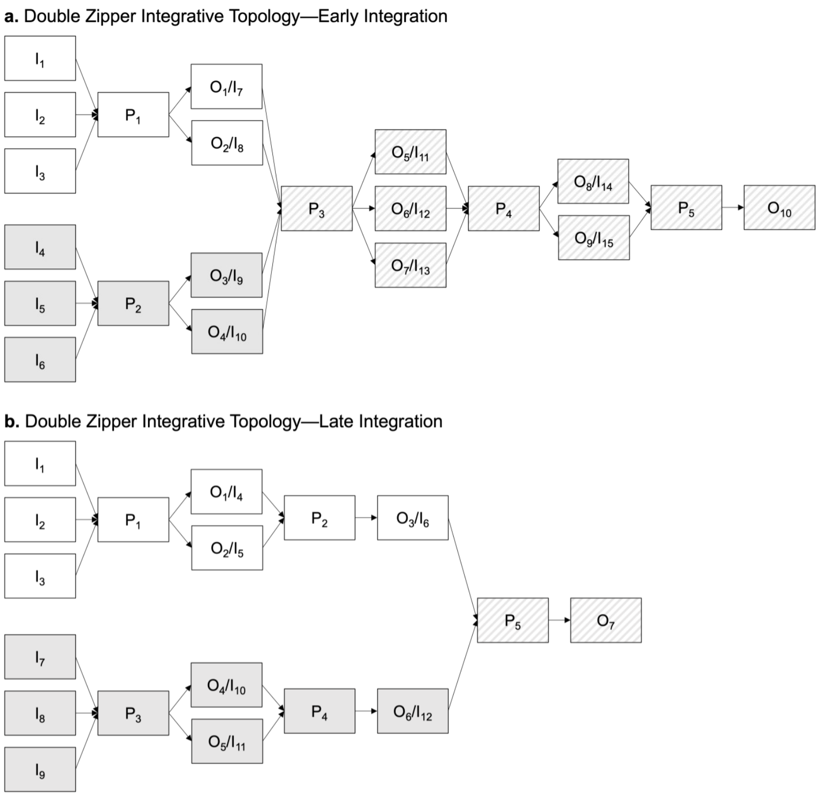


Figure 7. Stacked Zipper Topologies, Each Consisting of Two Zipper Pathways. Cross-Hatched Components are Part of Both Pathways. (a) Integration of the Two Zippers Early in the Pathways, and (b) Integration of the Zippers Late in the Pathways



5. Usefulness of Integrative Topologies

As mentioned above, identifying or observing can reveal not only what integrations are involved (the parts) but also what properties their connected structure might have (the whole). Integrative topologies can therefore be used to teach, plan, facilitate, describe, and evaluate integration. I will give an example of each use in turn.

5.1. Teaching Integration

When teaching or training others how to integrate disciplinary contributions, it is important to scaffold the skills so that learners do not become overwhelmed. Integrative topologies can serve as a scaffolding tool. Like chemical equations, which can be used in different ways at different levels of learning, integrative topologies can be used to introduce the general concept of crossdisciplinary integration, to explore how integrative pathways unfold, or to help learners design their own integrative pathways.

This focus on multiple integrations can augment existing approaches to teaching integration. For example, integrative topologies can be used to work through the integration tasks Repko and Szostak (2020) propose. For some projects, it may take several integrations to create common ground and construct a more comprehensive understanding (Keestra et al., 2022). Integrative topologies demonstrate that this is not only permissible but maybe even wise, creative, and fun.

As a more specific example, blank versions of Figures 2 through 7 can be used as graphic organizers to teach interdisciplinary writing (Boix Mansilla et al., 2009; Knight & Thompson, 2022). The graphic organizer would help writers plan and show their work in competencies such as:

- Including insights from two or more relevant disciplines
- Using an "integrative device or strategy" (an integrative mechanism), and
- Balancing the contributions of the various disciplines (Boix Mansilla et al., 2009).

The topologies clarify which insights are being integrated and how, which helps both the student and the teacher. As with any worksheet, students and teachers should guard against the temptation to fill them out blindly. They are useful only insofar as they support critical thinking.

5.2. Planning Integration

Teams can use an integrative topology to plan a research project. This will help identify what expertise is needed when and how it will be integrated. As is true when developing any interdisciplinary research plan, sketching such a topology before completing the work requires basic familiarity with varieties of disciplinary knowledge, their affordances, and their relevance to the research question (O'Rourke et al., 2019; Repko & Szostak, 2020). Basic familiarity with the relevant disciplines is more attainable for teams with a history of working together, teams with at least one member with a crossdisciplinary background, and teams with integration experts (Hoffmann et al., 2022, 2024). Such teams will be able to create more specific topologies than teams without these characteristics. Figure 8a shows an example topology from a participatory research project supported by the Michigan Institute for Clinical & Health Research at the University of Michigan.[6] In this example, a series of empirical results are

6 This example was created while the project was underway. It is a modified and more specific plan than was included in the project's proposal. Yet, it could be even more specific, naming the integrative relations involved in each integrative process.

combined through several integrative research methods. Such a topology can then be included in the proposal or internal documents to demonstrate and plan intentional, feasible knowledge integration.

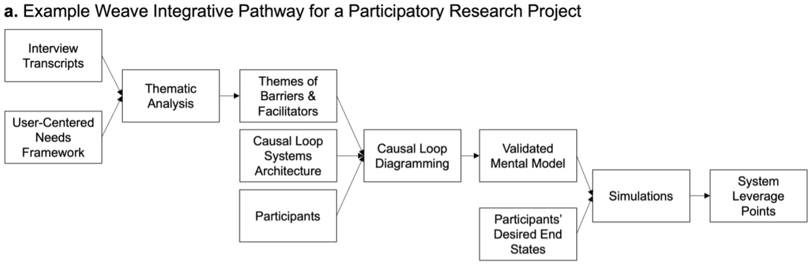
A topology could replace or supplement a logic model; both use IPO schema and are thus compatible (Figure 8). A logic model often collapses all inputs, processes, and outputs into their respective columns, but an integrative topology will show how processes are sequenced and what intermediate deliverables will be produced. The logic model takes less space but hides the relationships between intermediate steps, and in fact enables teams to neglect planning for them. Both visuals can therefore be useful. Of course, as with any plan, it is important to remember that the plan may need to change during implementation. The plan will also likely become more specific as research choices are made and collaborators learn by doing. This brings us to ongoing use of a topology while facilitating integration.

5.3. Facilitating Integration

Let's imagine the team above has been funded; their plan for integration was impressive and now it's time to get to work. At an early team meeting, a facilitator—ideally an integration expert—can post the team's integrative

Figure 8. Two Ways of Planning for Integration in a Participatory Research Project. (a) Example Weave Integrative Pathway. Note Explicit Inclusion of Participants in Second Integrative Step, and (b) Example Logic Model for the Same Project

a. Example Weave Integrative Pathway for a Participatory Research Project



b. Example Logic Model for the Same Participatory Research Project

Inputs	Activities/ Processes	Outputs	Short Term Outcomes	Mid Term Outcomes	Long Term Outcomes
• Funding • Researchers • Participants • Causal loop diagramming software	1. User-centered needs interviews 2. Thematic analysis to identify barriers & facilitators 3. Causal loop diagramming for systems mapping 4. System simulations	1. Themes from Interviews 2. Causal loop system map 3. Simulation outputs 4. List of system leverage points	• Stronger relationships/ trust with participant population • Deep understanding of participant experience of the system • Direction and enthusiasm for collective action	• White paper to raise awareness of leverage points • New working groups to tackle leverage points	• Greater collaborative capacity to improve participant access to services

topology plan on the wall or screen. They can even re-draw it in erasable chalk or marker to emphasize that it can be changed. Then, several exercises become possible. First, the team can discuss if their proposed topology still resonates; perhaps individuals draw their own modifications and then share. Second, the facilitator can walk the team through creating a roadmap for each step of the topology, listing the specific people, resources, and timing needed for each. Parameters from the IPO model could guide this listing (e.g., quantity, scale). Third, the team can pull the intermediate and final outputs from the topology to develop a timeline of deliverables, and the facilitator can help them reference or adjust the topology during the conversation. In such conversations and afterward, the topology could serve as a boundary object by which collaborators can coordinate their expertise when complete consensus or shared knowledge is not possible (Merck et al., 2023; Star, 2010; Star & Griesemer, 1989).[7]

5.4. Describing Integration

Individuals in several research, teaching, or support roles may be interested in describing how integration is unfolding or has been accomplished. For example, the team facilitator above might want to know how the team is progressing. An integrative topology could be sketched mid-stream to make sense of progress. More formally, those who research crossdisciplinarity seek more precise ways of modeling integrative cases. When introducing the weave, zipper, and chain above, I showed how these can be used to describe examples of integrative research from the literature. Moreover, since integrative topologies are built from IPO instances of integration (and perhaps disintegration or other processes), analysts can describe the integration in detail by including integrative relations and IPO parameters (e.g., quantity of inputs, nature of integrative relation, scale; O'Rourke et al., 2016) and by describing the full socio-materiality of the integrative processes and mechanisms.

5.5. Evaluating Integration

Integrative topologies can also support judging the merit, worth, or significance of integration in a single case or across cases. The topology is a structure, and so cases can be compared structurally even if their contents vary. In so doing, those evaluating the work may decide that some structures are more elegant, difficult, comprehensive, fruitful, or otherwise more valuable or significant than others. Compare, for instance, Figures 5 and 6. Some may see the topologies in Figure 5 as more elegant than their counterparts in Figure 6,

7 Using a topology as a boundary object could be a good reason to keep the integrative processes rather vague.

but the topologies in Figure 6 may seem more of an achievement than those in Figure 5. Just as some proofs of the Pythagorean Theorem are more elegant, some more teachable, and some more difficult than others, integrative topologies may also vary in their significance for different reasons, even if two topologies result in the same output.

When evaluating a single case, evaluators may assign worth based on whether the final integrative topology that was executed matches, or diverges from, the topology that was planned—depending on our values for adaptive planning. By comparing many cases, evaluators may be able to show that certain topologies yield certain important outcomes, justifying a conclusion that some topologies are more valuable than others. Knowing more about the merit of different topologies would be helpful for not only looking back on a project but also for looking forward, as when prospectively evaluating grant proposals for integrative research.

5.6. Use of Integrative Topologies

In summary, integrative topologies are useful analytically and heuristically. They can be used by both integration experts and scholars new to crossdisciplinary practice. Many approaches to working with integration rely on metaphors such as linking, blending, and bridging. Integrative topologies complement the gestalt benefits of these metaphors by emphasizing the internal structure of integration. Using topologies requires distinguishing inputs, processes, and outputs, especially understanding what the intermediate outputs are. Thinking critically about what could count as an integrative mechanism, process, or relation will also help put the topologies to work—even if, as a boundary object, those are left underspecified at first. With care and creativity, integrative topologies can be conceptual and visual tools for teaching, planning, facilitating, describing, and evaluating the buzzing, blooming confusion that is knowledge integration.

6. Future Philosophical Research

In this article, I have introduced the concept of integrative topologies and how it might be useful. This introduction raises new philosophical questions about integrative topologies and about integration more generally.

First, what other topologies are possible beyond weaves, zippers, and chains, and what are their properties? We may find answers in three disparate places, among others: (1) graph theory, (2) fiber arts, and (3) empirical studies of integration. Graph theory may provide other topologies that directly transfer to integration or mathematical methods that can be used to derive and study integrative topologies. A set of integrative pathways can be treated as a special kind of network with restrictions on which nodes can connect with others and in which order. Since outputs can become inputs, these two can be treated as a single type of node or "mode" in network terms. They cannot connect to each other but only to processes, which are a second mode. Further, the connections from inputs to processes to outputs are directed. Thus, this is a 2-mode directed network. There may be additional constraints on which processes can connect with which inputs and outputs based on the integrative relations or mechanisms powering the processes. The IPO model notes parameters that describe aspects of integration (namely, commensurability, scale, and comprehensiveness), and these parameters may also limit how integrations can connect. Equations and models could be developed to describe the possibility space for these kinds of networks. At the same time, network topologies like stars and meshes that are not technically possible with integrative pathways could nevertheless provide inspiration as metaphors.

Metaphorical inspiration could also be drawn from the fiber arts. Indeed, integration has long been described in terms of weaving and knitting. Knot tying crafts such as macramé may be especially fruitful metaphors for integrative pathways. How could knot tying and weaving patterns translate into integrative topologies?

And then, through empirical study of integration, we may look to the ingenuity of crossdisciplinary practice for more integrative topologies. Necessity being the mother of invention, it would not be surprising if practitioners created new forms of integrative topology to address unique crossdisciplinary problems. Kristine Lund, for instance, asked lead investigators to create a visualization of crossdisciplinary integration in their projects. Later, she introduced visual prototypes of the weave, zipper, and chain topologies to the lead investigators and asked them how these topologies applied to their visualizations, if at all (Lund et al., 2023).[8] The investigators and interviewer together identified novel variations of these topologies, such as a weave wrapped around a chain.

A second area for further philosophical research concerns the nature of integration. First, what could topologies reveal about how different types of integration build upon each other through integrative pathways? For example, O'Malley and Soyer (2012) distinguish between methodological, data, and explanatory integration. Can the outputs of methodological integration directly become inputs for data integration, or must they undergo some transformation first? Trying to map the topology of such a pathway could reveal more about the nature of these different types and about integrative pathways more generally.

Another question about integration arises: How are integrative instances, mechanisms, pathways, and trajectories related? I have proposed definitions

8 Note: The chain schema presented was different than that presented in this article, and technically invalid.

for each, but they deserve further exploration. If these are indeed distinct aspects of integration, then they illuminate integration as a socio-material phenomenon that unfolds over time in different patterns. These patterns—patterns of mechanism (yet to be named), patterns of pathways (integrative topologies), and patterns of trajectories (also yet to be named)—will have different properties that influence the integrative outcomes.

7. Conclusion

The concept of an integrative topology is a philosophical innovation that makes it possible to articulate the structural connections between multiple integrations. It enables a new, structural approach to understanding integration. In turn, each topology is a context-crossing, context-adaptable model of a complex integrative achievement. The example topologies described here can be used as they are, and they can inspire new forms. Integrative topologies support variety without dissolving distinctions: a few key rules about integrative inputs, processes, and outputs yield manifold combinations. These structures facilitate description of individual cases while enabling learning and comparison across cases.

Integrative topologies thus fill an important need in the practice and study of crossdisciplinarity. In the absence of structural models of connected integrations, practitioners and theorists alike expend tremendous effort generating new plans and explanations for any but the simplest, one-step integrative achievements. Each case must start from nearly scratch, either inventing new ways of connecting multiple instances of a general model of integration (e.g., Hoffmann et al., 2017) or building completely from the ground up (e.g., Nersessian, 2022). This *sui generis*, groundbreaking work is often confusing, intense, and lengthy. Many times, attempts still fall short of their potential. It is easier to describe the overall integrative achievement rather than how it was or will be constructed. It is easier to use metaphors and synonyms for integration than to specify the relations moving one integration to another. It is easier to generalize about integration writ large than to parse its internal structure. Integrative topologies are "cognitive jigs" (Cabrera & Cabrera, 2015, p. 85) that accelerate integrative work and open new theoretical and practical vistas. They are important new tools for integration experts, novices, and anyone concerned with complex combinations of expertise that drive innovation.

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