# Bridging the Divide: Reconciling Quantitative System Dynamics and Qualitative Systems Thinking Causal Loop Diagrams (CLDs) on Shared Defining Characteristics and a Common Order

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**Abstract:** This note continues a dialogue requested in a recent issue discussing the identity of system dynamics as a field. Although quantitative system dynamics and qualitative systems thinking causal loop diagrams (CLDs) are common in the field, significant tensions remain on what is, or is not, appropriate to consider system dynamics. Building upon recent work identifying five defining characteristics of quantitative system dynamics models, we propose a path of reconciliation by showing how qualitative systems thinking CLDs share all but one of the same characteristics. This commonality creates an opportunity to arrange a common order, similar to an architectural order, of the constituent parts, using the metaphor of a stonemasonry bridge and an analogy to the hierarchy of matter. From this ordering arises a set of key first principles common to the order and both kinds of models: deconstruction and subsummation across levels in the order, scalar indifference to aggregation or disaggregation, and bridging between mental and mathematical equations. We show how, as the field matures, embracing metaphors and analogies as tools to facilitate the introduction of complex subjects by tying them to already-known topics can improve accessibility to new students and stakeholders encountering the field.

## 1 Introduction

Imagine two towns on either side of a deep, uncrossable valley. Separated by the space, they each conduct their daily affairs in their own ways, viewing the town across the gulf with equal parts curiosity and suspicion. Each community is equally mysterious to the other. However, what the towns share is the valley. Furthermore, what was once an obstacle can support a connection when a bridge crosses the gap. Two towns once separated now travel, trade, and interact, learning from one another across the bridge.

The valley in our field is a complex system. The towns on either side of it are quantitative system dynamics simulations and qualitative causal loop diagrams. The authors, in pursuing our PhDs in system dynamics, we were both taken aback that the common interest in complex systems served as a barrier between the two towns, when it could have been a bridge. Answering a call by the SDR to embark on a dialogue of the identity of our field[1], continuing our effort to make that identity one of reconciliation rather than opposition[2], and building upon recent work defining a set of characteristics for quantitative system dynamics simulations, we wish to begin building a bridge between these two towns.

We begin our architecture efforts with a clear purpose and scope boundaries: bridging the divide between quantitative system dynamics simulations and qualitative systems thinking causal loop diagrams. We intend not to comment on or reconcile other simulation or systems thinking tools than these two. Though we think that is a much-needed discussion and hope others continue to do so, we are focused only on these two methods. We illustrate this challenge in Figure 1 by leveraging a modified illustration of the Hadlock Brook Bridge in Acadia National Park found in Maine, US, published by the National Parks Service[3].

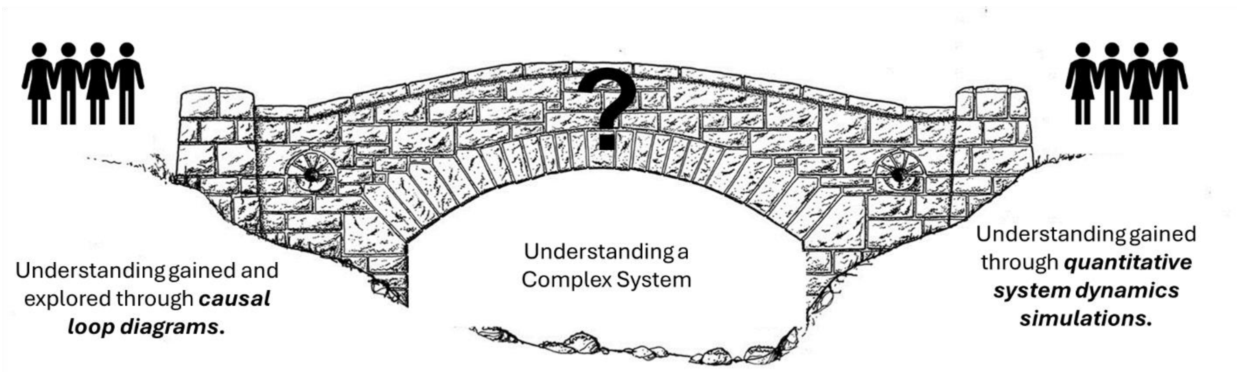


*Figure 1: Purpose - What Can Bridge the Divide?*

From afar, our bridge in Figure 1 looks like a solid seamless structure of a stone bridge. However, when we look closer different parts emerge. We can see different shaped bricks and stones. These parts form what is known as an architectural order. We begin our construction by first describing an architectural order, then showing how quantitative system dynamics and qualitative systems thinking CLDs already have the attributes of architectural orders.

Next, we demonstrate that quantitative system dynamics and qualitative systems thinking CLDs share a common set of defining characteristics with only one minor variation. This basis of shared, defining characteristics enables reconciliation across the two orders to combine them into one. We present this reconciled order next, leveraging both the metaphor of the order of a stonemasonry bridge and an analogy to the hierarchy of matter. This hierarchy organizes physical matter from its smallest form in elementary particles to its larger form in chemical compounds.  Of course, all metaphors and analogies have limits, and we provide these symbolic representations not to communicate what a thing is but to provide a known familiar pathway to explore the unfamiliar. Afterward, we briefly discuss some key principles that we think are elevated by this single reconciled order and conclude with a brief discussion of the implications and opportunities of such bridging.

Such a framework can make the foundations of the field more accessible to students beginning their journey, explainable to stakeholders with wicked mess problems to solve, and assist in integrating with other developing technologies of data science. AI, and also experienced modelers working in either town can benefit from a reconciliatory, rigorous, and explicit framework that’s useable as a confidence-building test. Though we approach this from the perspective of structuralism, our goal is to increase interaction and travel between the towns rather than keeping them divided[2].

## 2 Order of Structure in a Stonemasonry Bridge

In architecture, an order is a "certain assemblage of parts subject to uniform established proportions, regulated by the office that each part has to perform [4, p. 680]". In describing a stonemasonry bridge used in the metaphor of our introduction, an order would consist of keystones and ringstones, masonry bricks, capstones, and a roadway, as depicted in Figure 2.

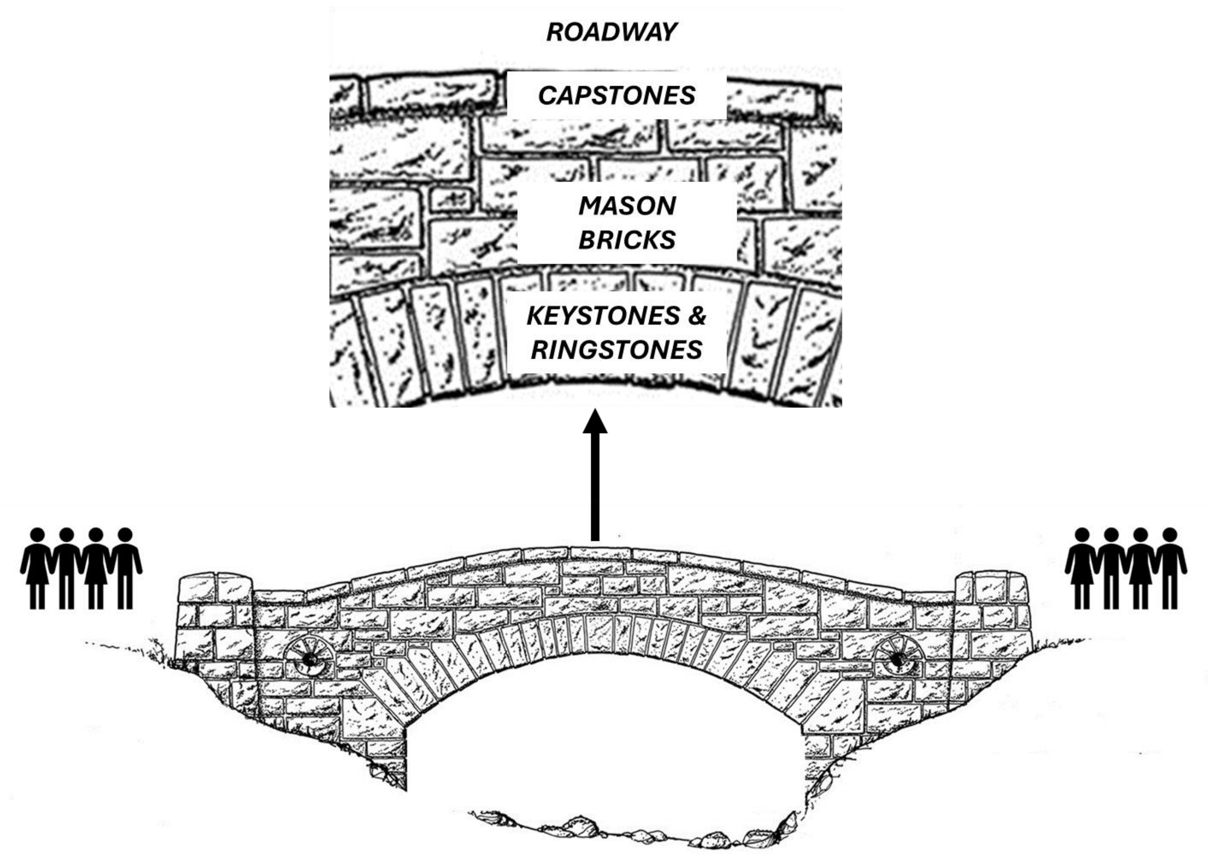


*Figure 2: Order of Architecture for a Stonemasonry Bridge*

Keystones and ringstones have a special form that, when conjoined, creates an arc curve that both supports the bridge and provides its aesthetic marker. Masonry bricks fitted atop this foundation and one another form the bulk of the bridge. These bricks are topped by capstones, forming a smoother finish, and finally, the last layer is the roadway itself. To the uninitiated eye, it looks like a single stone edifice. However, the parts become clear with a closer eye to detail and minimum instructions. Both visual form and some education clarify the unclear relationship between different parts of the structure, serving as falsifiable criteria for determining the inclusion or exclusion of a given part of a level in the order. Moreover, it allows arranging the parts of order so that subordinate structures can combine to create higher-order structures, and likewise higher-order structures can be deconstructed into subordinate parts without fidelity loss at any level of the order. A bridge's order is scalar indifferent to the size of the bridge, and the same arrangement of parts exists in both small pathway bridges and large stone spans.

This section identifies the structural parts in each order for both quantitative system dynamic models and qualitative systems thinking CLDs. As these structures are well documented elsewhere, we provide only a cursory overview with references for further reading. In the intervening decades, the field recognized these parts not as independent, but as levels of the structure that the combination of basic building blocks of feedback loops in the "feedback system", beneath which lie "stock-flow structures", and beneath those are "underlying equations make up the structure of the model [5, p. 35]."

### *2.1 Structural Order in Quantitative System Dynamics Stock & Flow Models*

There are four levels in the order of quantitative system dynamics models. The lowest level of its 'constitutive structures' are stocks, flows, auxiliaries, and constants [5, pp. 85–87] and their combinations. When these combinations loop back and connect upon themselves, the second level of a feedback loop arises. Two additional levels exist above that basic building block of a feedback loop. The third level is abstracted micro-structures, a specific combination of stock and flows in a feedback effect representing "deeper, more fundamental," describing foundational laws similar to Ohm's and Newton's laws [6, p. 94]. Today these are more commonly called generic structures, a term we use going forward. Generic structures were ubiquitous in systems that Forrester saw as valuable in "supporting a fully-specified simulation model which generates a single, commonly observed behavior mode [6, p. 96]." The final fourth level began with the market growth model and focused on representing the causal interactions of feedback loops in a particular class of problems [6, p. 92]. This library then grew with the other general models, including urban dynamics [7], project dynamics[8], and the evolution of world models [9]. As general models, canonical models serve as "system examples," often by combining abstracted micro-structures ubiquitous to the field and domain-specific structures helpful in illuminating a feedback mechanism within a class of problems [10, p. 5]. Canonical models should be "fully specified" and capable of generating "significantly different modes of dynamic behavior depending on the parameters and policies employed [6, p. 91]."

### *2.2 Structural Order of Qualitative CLDs Quantitative System Dynamics Models*

Around the same time Lane began defining canonical quantitative system dynamics simulations, Meadows and others were developing a divergent yet parallel hierarchy of a structural order for qualitative CLDs. This parallel structure also consisted of four levels within its order. The goal of this adjacent approach was "computer-free systems insights" that everyday people could remember and act upon in navigating a complex society [9, p. 98]." While mathematical equations connected constitutive elements of stock and flow models, CLDs used mental equations based on logic indicated by symbols of causal links and polarities. However, despite one relying on mathematical equations and the latter on mental reasoning, the purpose remained the same to see not just a "system… of interconnected elements" but also that to "understand things, we take them apart and study the pieces [9, p. 101]." The second level of qualitative CLDs is the same as quantitative system dynamics, a series of connections that loop back on itself to create a feedback loop [9, p. 102].

The third level of qualitative CLD structure, known as a system archetype, consists of one or more feedback loops operating individually or in combination with another feedback loop. Just as in quantitative system dynamics, the feedback loop became the item of most interest of study in CLDs. Each feedback loop had substructures underpinning it. The stocks, flows, auxiliaries, and constants in their connected mathematical equations of quantitative system dynamics models corresponded to asserted phenomena, causal links, and polarities of qualitative CLDs. Both serve the same purpose of making the structure of parts explicit beneath any given feedback loop consisting of "the variables and the direct causal relationships between them [5, p. 36]."

The handful of system archetypes identified by Meadows and Runge [9], [11], and others were developed and introduced to a much wider audience with an appendix in Peter Senge's global bestseller, *The Fifth Discipline* [12, pp. 389–400]. System archetypes aim to capture recurrent structure patterns and explain commonly occurring dysfunctional phenomena [6, p. 100].

Given their qualitative nature, the precise number of system archetypes has varied from as low as 8 to a number less than 30. Wolstenholme's hypothesis proposes that based on the inherent logic of these basic building blocks, there could only ever be four truly generic problem two-loop archetypes: underachievement, out of control, relative achievement, and relative control [13, p. 11]. Adding a link to the four problems of two-loop archetypes results in a combination of eight generic archetypes. Whatever the number of archetypes, from the very beginning, modelers referenced higher-level structure above the archetype, similar in purpose to the canonical model called a system paradigm. Like canonical models in quantitative system dynamics, system paradigms of qualitative CLDs look at classes of problems, providing a "useful way of looking at some of humankind's most persistent problems - hunger, poverty, environmental degradation, and war - problems that do not seem to be solvable when looked at from older and more familiar viewpoints [9, p. 98]." Interchangeability of system paradigms with canonical models became apparent as modelers distilled canonical models to their constituent system paradigms of interacting system archetypes.

### *2.3 Often paired but rarely reconciled.*

These adjacent orders are often paired, at times referred to in a basket of terms distinguishing by use as: "(i) predictive simulation models; (ii) descriptive integrated models; and (iii) participatory and shared vision models [14, p. 2424]" or simply as qualitative mapping and quantitative simulation modeling [15, pp. 441–444]. The use of the two types of structure, often in tandem, has become ubiquitous in the field, and both feature prominently in most common textbooks [16], [5].

However, the tension between these orders has been one of the dominant topics of debate over the past thirty years [17, pp. 149–150]. Part of this tension is that there are valid use cases for each form of structure, as qualitative mapping without simulation can be faster and easier to create to "change minds [15, p. 441]." However, the more straightforward application of this approach may "lead toward their overuse [15, p. 441]." Technical concerns continue that the inexactness of CLDs can create misunderstandings on how change operates when the modeler does not distinguish whether a feedback phenomenon is a flow or a stock. The tension in the field emerged again in the publication by SDR of a note defining essential characteristics of quantitative system dynamics models[18]. In a recent note proposing defining characteristics of quantitative system dynamics models, editors solicited commentary, and much of the submitted material focused on the concern that by defining essential characteristics of quantitative system dynamics models, the authors were, by default, excluding qualitative systems thinking CLDs as being valid[1].

## 3 Bridging the Divide – Proposed Reconciliation

However, that same note provides a basis for reconciliation. The note sought to capture 'defining characteristics' of quantitative system dynamic simulations with an intent to "i) capture the core philosophy of system dynamics, (ii) describe the theoretical and practical principles that make system dynamics modeling unique, and (iii) apply to historical work but be flexible enough to hold as technical capabilities progress[19, p. 4]" The note excluded at the outset addressing qualitative methods, such as systems thinking[19, p. 1].Nevertheless, with only one small change, these defining characteristics can also capture the philosophical principles and are flexible enough to encompass both historical and future work of systems thinking qualitative CLDs, as shown in Table 1.

*Table 1: Defining Characteristics of Quantitative System Dynamics Models aligned with Qualitative Systems Thinking CLDs*

| **Defining Characteristics of Qualitative Systems Thinking CLDs** | **Defining Characteristics of Quantitative System Dynamics** |
|---|---|
| Models are based on causal feedback structure | Models are based on causal feedback structure |
| Accumulations and delays are foundational | Accumulations and delays are foundational |
| Models are based *on mental equations* | Models are *equation-based* |
| Concept of time is continuous | Concept of time is continuous |
| Analysis focuses on feedback dynamics | Analysis focuses on feedback dynamics |

Both methods aim to create a model representing an operational causal perspective to understand how complex systems work [20], [21]. The only difference in the defining characteristics is how the modelers handle the equations representing those operations, mathematically or mentally.

With this common set of characteristics, we can locate our materials in a bridging framework, tying them into the analogous structural materials of a stone mason bridge, the hierarchy of matter, and the specific structural elements identified above. In this way, our proposed hierarchy of systems structure advances towards the criteria we have established, comparable in analogy to the existing hierarchy of matter in Table 1[22].

Table 1: Order of Structures Across our Framework

| **Bridge Metaphor** | **Hierarchy of Matter Analogy** | **Systems Thinking CLD** | **Quantitative System Dynamics Models** |
|---|---|---|---|
| **Keystones & Ringstones** | Elementary Particles | Feedback Phenomena | Stocks, Flows, Constants & Auxiliaries. |
| | Sub-Atomic Particles | Causal Loop Parameter, Causal Link & Polarity. | Connected Stocks & Flows |
| **Mason Bricks** | Atoms | Feedback Loop | Positive and negative feedback loops |

| | | | |
|---|---|---|---|
| **Capstones** | Chemical Elements | System Archetype: One or more feedback loops are presented as a Causal Loop Diagram (CLD). | Abstracted Micro-Structures or Generic Structures: Combinations of stocks, flows, constants, and auxiliaries. |
| **Roadway** | Compounds | System Paradigms: Combinations of more than one system archetype presented as CLD. | Canonical Models: Computational simulations represent a class of problems. |

We do not use these metaphors and analogies to be perfect descriptions of granular concrete or stone or the physical sizing, electromagnetic, or chemical properties of the hierarchy of matter. Instead, they are used to facilitate understanding and education. The metaphor of order provides an introductory framework to understand how the constituent parts of a bridge constitute an order, and so can the constituent parts of quantitative system dynamics and qualitative systems thinking models. Lower levels of order support the higher levels. Furthermore, the higher levels are not independent objects, but rest upon the foundations of the lower orders. The metaphor further illuminates the purpose of ordering the parts as an artistic exercise and facilitating travel and greater interaction over the valley of an unknown complex system.

The analogy of the hierarchy of matter provides insight into the relationships among these parts. Higher-level parts subsume into their structure the lower-level parts. In the reverse, deconstructing higher level structures on the hierarchy of matter results in exposing their lower-level subordinate parts. Elementary particles form into atoms. Atoms never go away. They can be combined to form chemical elements, classified by their weight and number of electrons on the periodic table. Chemical elements combine to form stable compounds. In reverse, a stable compound can be separated into its chemical elements, and the atoms that comprise those elements can be deconstructed further into elementary particles.

We recognize that all analogies have limits. However, below, we leverage the metaphor of the bridge and analogy to the hierarchy of matter to introduce and facilitate understanding of our proposed reconciled order of systems structure bridging quantitative system dynamics modeling and qualitative systems thinking CLDs.

## 4 A Reconciled Order

We present a reconciled order visually in Figure *3*. We use the metaphor of the bridge and the analogy of a hierarchy of matter as the central construct to frame the order, so we present these terms in a middle segment of the diagram across levels 1-4. Each level includes the architectural term of the order in the metaphor of the bridge and then, in parentheses, the term from the analogy of the hierarchy of matter. On the left of the diagram, we provide the equivalent constituent parts to the proposed order of qualitative systems thinking CLD terms, and to the right, we provide the same for quantitative system dynamics models.

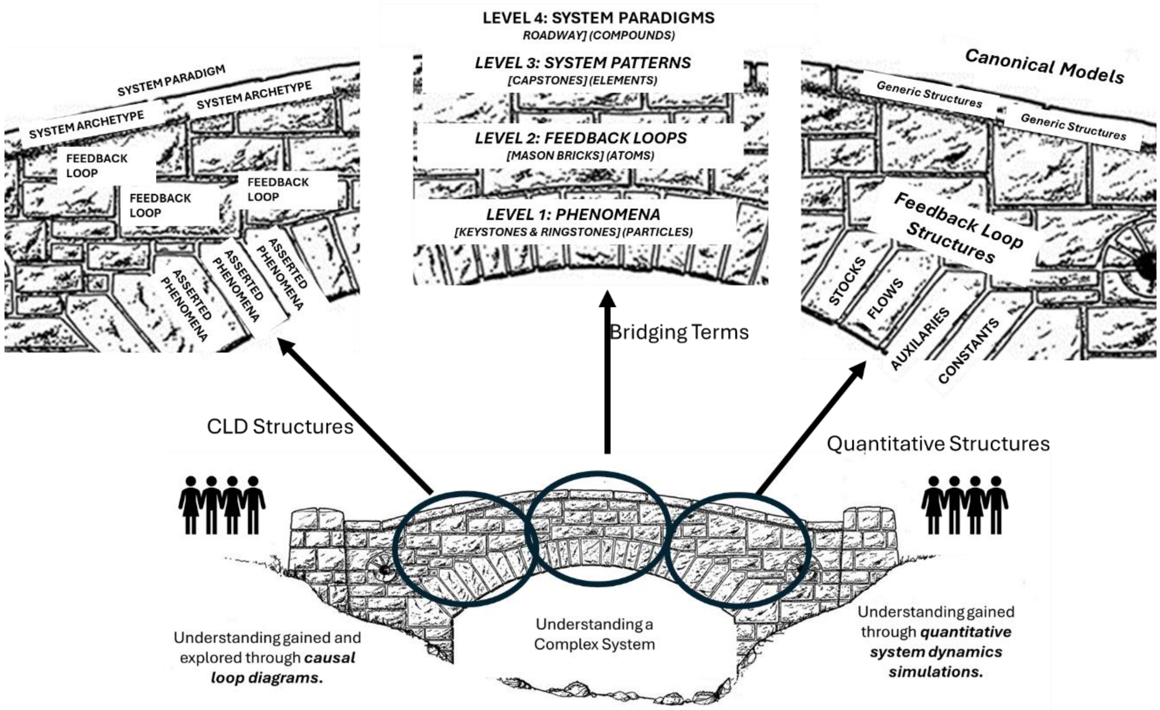


Figure 3: Reconciled Order between Qualitative Systems Thinking CLDs and Quantitative System Dynamics Models

### *4.1 1st Level: Phenomena*

In our bridge, the lowest part of the arch are the keystones and ringstones, and the fundamental building blocks of all matter are elementary particles. Likewise, we begin at the lowest level in the hierarchy of matter, the phenomena a modeler seeks to represent which serves both as foundation and constituent subsumed part in all levels that come after. We use the definition of "phenomena" in both its dictionary meaning as "a fact or event of scientific interest susceptible to scientific description and explanation" as well as in its sense as the purpose of system dynamics is to "seek an endogenous explanation of phenomena [16, p. 95].

Elementary particles in the first level, the keystones and ringstones, answer four questions. Three of these are common to both methods: What phenomena does the model represent? How are the phenomena represented in equations? And, in what order of operations are those equations computed? The fourth question is the only part where the methods differ and returns to the one defining characteristic with differences between the two. How are equations computed through mathematical or mental means?

Modeling in quantitative system dynamics, and thus mathematical equations, the first level phenomena appear as stocks, flows, constants, and auxiliaries identified by Forrester [23, pp. 74–75] and later textbooks [5, pp. 85–87]. These structures and their connections convey the mathematical equations and the order of operations they should occur, making the model accessible to mathematical analysis and computer simulation software.

When modeling in qualitative systems thinking CLDs, and thus mental equations, the first level phenomena are represented in plain language terms accessible to readers' mental models, regardless of mathematical acumen or ability to computer mathematical operations. The causal links and polarities of CLDs convey the order of operations and specific functions of these mental equations. To be clear, we distinguish between mental equations and mental calculations. As we describe a CLD we often say as X increases, Y increases or decreases. This is an equation that conveys a relationship Y is function of (X) or Y is directly proportional to X. In the case of as X increases Y decreases; Y is inversely proportional to X. Accordingly, CLDs include simple implicit mathematical relationships that are mentally processed, hence our use of the term "mental equations" and not “mental calculations” are as we are not performing explicit mathematical operations. For example, a goal seeking feedback loop has a mathematical relationship of a simple first order controller, but when presented in a CLD that feedback loop is not expressed as an explicit mathematical equation, but rather a mental equation.

Although it can seem counterintuitive to those accustomed to mathematical equations, the use of qualitative CLDs with their mental equations has merit. There are more problems of interest existing in complex systems to study than there are complete libraries of mathematical equations to study them with. Qualitative CLDs allow considering the whole of a system of interest bounded by the problem statement versus the smaller set of interactions that can be expressed in mathematical equations when circumstances merit. Examples of these circumstances are numerous: studying phenomena that are novel, deal with high ambiguity or uncertainty, are hard to measure, or involve the interaction of mental models captured best by ‘descriptive knowledge’ of participants in those systems[24, p. 157]. A mental equation can accurately capture a structural relationship even when the exact parts of an equation and their specific numerical values necessary to perform a numerical calculation remain unknown. Nor does starting with qualitative systems thinking CLD preclude advancing to quantitative system dynamics as circumstances merit[24, p. 159]. One of the contributors to this work identified a novel hypothesis in radicalization leading to public mass killings from qualitative systems thinking that has since been studied more formally in quantitative system dynamics[25], [26], [27]. The systems thinking model may have been ‘wrong’, but it was still useful for identifying the hypothesis [28]. Ultimately numerical expressions themselves are just models of a complex real-world phenomena, subject to being simultaneously wrong and yet still useful. Experienced practitioners in both methods understand the pros and cons of both approaches, can and should conduct tradeoff evaluation of risks versus utility in selecting a method.

Because despite this key difference in how equations are represented and computed, the first-level phenomena share the same purpose regardless of method: To represent an assertion of an operational causal understanding of a complex system [20], [21], or how does a complex system work.

Our falsifiable definition of the first-level phenomena is that it must subsume any combination of equations necessary to reproduce the asserted phenomena. In quantitative system dynamics, this may explicitly list elementary structures: stocks, flows, constants, and auxiliaries. In qualitative systems thinking CLDs this may be a plain-language feedback phenomena inclusive of these interactions. In either case, if an asserted phenomenon is supposed to represent a pathway creating change to the system's behavior, then the representation must be capable of producing that change under the normal rules of either method. This makes the choice of what elementary structure to include in any feedback phenomena based on the model's purpose and the amount of aggregation or disaggregation in scale or scope that best suits that purpose. For example, in a population model, a scale question of aggregation asks what the best size of population to put in each stock (e.g micro, meso, or macro populations) while scope questions of aggregation ask whether groups should be mingled within a single stock or broken apart into multiple stocks for clarity.

### *4.2 2nd Level: Feedback Loops*

The hardest part of reconciling quantitative system dynamics models and qualitative systems thinking CLDs is now out of the way. Because parts in an order build upon one another and levels in the hierarchy of matter subsume one another, each successive level in the order builds on what came before. In a stonemasonry bridge, masonry bricks rest atop keystones and ringstones. In the hierarchy of matter, elementary particles combine to form atoms.

In our reconciled order, the masonry bricks and atoms are feedback loops. These are the basic building blocks of most models, whether quantitative system dynamics or qualitative systems thinking CLDs.

The falsifiable definition of a feedback loop is that it must consist entirely of feedback phenomena and, within its structure, evidence of endogenous feedback. Endogenous means each feedback phenomenon must possess a causal link to another feedback phenomenon and be linked from phenomena, not itself. When combined, all links create circular effects along the causal chain.

A test of this criterion is to select any feedback phenomena in the loop and trace its causal pathways until arriving at the starting phenomena. Suppose a single path does not eventually return to the selected phenomena. In that case, there is no endogeneity, and if there is more than one path, it is not a single feedback loop, but a system archetype (the next highest level of the order.) Likewise, the isolated phenomena structure, providing causal influence into or out of a system, is not appropriate at this level and is also reserved as a feature of the next level of the order. There are only two feedback loops: positive or reinforcing and negative or balancing. The determination of these is left to the reader's exercise as the methods are well known. We do not need to repeat those methods here other than to note that the falsification test at this level is the proper application of methods. For example, for systems thinking qualitative CLDs, if an asserted feedback phenomenon is sufficiently vague or the polarity is unclear, it fails falsification and should be reworded, split apart, or otherwise remedied. Likewise, for quantitative system dynamics models, feedback loops that do not demonstrate unit dimensionality, and first-order control fail falsification except for most problems under consideration. These examples are not a full list, nor are they universal as rare cases may apply waiving each. What we mean however is the proper methods of the field for representing feedback structure, both as they are now and they advance in the future, are the falsification criteria for this level.

### *4.3 3rd Level: System Patterns*

System patterns are like the chemicals on the periodic table arrived at by combining atoms. Just like atoms form into different combinations to create chemical elements in the matter hierarchy, the two types of feedback loops can combine to create larger structures. Like chemicals on a periodic table, system patterns are finite in number, but ubiquitous in their frequency and, when combined, can support the building blocks for more extensive, more complex combinations in forming organic and material compounds. In quantitative system dynamics, models' system patterns are known as generic structures. In qualitative systems thinking, CLDs, system patterns are known as system archetypes. Nevertheless, both serve the same role as system patterns, and we use that term forward. The falsifiable rules of system patterns, whether system archetypes or generic structures, are:

1. It consists of one or more feedback loops, and may include one or more phenomena structures outside the feedback loop which serve as exogenous variables to the feedback loops.
2. It is not just a representation of another archetype or generic structure, swapping virtuous or vicious labeling for the positive/reinforcing loop.
3. It does not include two or more known system archetypes or generic structures.
4. It has objectively different feedback structures from other system archetypes and generic structures and can produce objectively different behavior modes under the right conditions – even if some behavior modes are similar.
5. A simpler structure cannot represent the portfolio of behavior modes.

The falsification of system patterns in the context of system archetypes we present here is not to settle the Wolstenhome hypothesis[13], but recognize that at some point, new combinations of positive and negative loops will either replicate existing system patterns or be combinations of existing system patterns. These are the definitions of system paradigms (see below).

### *4.4 4<sup>th</sup> Layer: System Paradigms*

System paradigms are akin to compounds in the hierarchy of matter, formed when chemical elements on the periodic table combine. The number of compounds is unknown because of the large number of chemicals and the various sequences of connections available. Likewise, the $4^{th}$ and final level of our proposed reconciled order has an uncertain limit in the number of ways system patterns can combine into structures. In both quantitative system dynamics simulations and qualitative systems thinking, CLD system patterns of generic structures or system archetypes combine and recombine in bewildering variety to create a rich expression capable of representing all the problems modelers may find of interest to study.

For quantitative system dynamics simulations, system paradigms may also be known as canonical models, while for qualitative systems thinking CLDs, the term remains system paradigms. The falsifiable rules of canonical models and system paradigms are similar; a canonical model must include two or more abstracted microstructures connected in feedback, while a system paradigm must contain at least two or more system archetypes. To this minimum, any number of individual constituent elements may be added as bridges in from or out to another system outside the boundary definition of the problem. The behaviors of canonical models and system paradigms depend on which particular feedback loops are dominant at any point in time, allowing both to demonstrate– under various conditions – the behaviors of many kinds of lower-level structures subsumed within it, as well as novel behavior arising from the interaction of the whole of the archetypes contained within it. Since there is no outer limit to the number of system patterns of generic structures or system archetypes representable at this level, modelers should carefully select boundaries relevant to the problem of interest. A canonical model represents the system paradigm in the computational form of stock and flow models. For example, the rework cycle structure exists within a more extensive project dynamics canonical model, a portion of one form commonly used in instruction [29].

## 5 Discussion of Principles of the Reconciled Order

Having arranged the reconciled order across the common defining characteristics and along four levels we present for discussion some first principles related to both the reconciled order, and potential for reconciliation and education. We begin with three first principles of the reconciled order itself. Although these concepts are not entirely novel to the field, we emphasize them here as beneficial characteristics amplified by the proposed order.

### 5.1 *Deconstruction & Subsummation Across Levels in the Order*

Deconstruction means that any higher-level structural representation could be broken into its constituent parts for examination if desired or requested. Modelers can distill system paradigms, system patterns, feedback loops, and phenomena. Likewise, subsummation means that structures can be built from the bottom level up with higher levels encompassing the lower. Whether starting with causal links and polarities and plain language terms in a CLD or the mathematical combinations of stocks, flows, auxiliaries, and constants, a modeler can arrange these to create feedback loops, system patterns either of system archetypes or generic structures, and system paradigms that combine system archetypes or represent canonical computer simulation models.

### *5.2 Scalar Indifference to Aggregation or Disaggregation*

All structures in the reconciled order are indifferent to scalar change, whether in aggregation or disaggregation. The stock of a small house's population and the stock of a country's population are still stocks; both are elementary structures of the first level of order. Likewise, a fourth level system paradigm can encompass the complicated geopolitical relations of many countries or the complicated domestic relations of two individuals working or living together. The form and function of the constituent part in a given level of the order creates distinction, not the level of scale of what is being represented by that level.

### *5.3 Bridging between Mental and Mathematical Equations*

Bridging represents the roadway facilitating travel between quantitative system dynamics and qualitative systems thinking CLDs in pursuit of understanding complex systems. At any order, the structure presented at one level of the order should be representable in its equivalent level. For example, modelers can distill a canonical model into a combination of system archetypes. Both represent a system paradigm, and the difference is in computation. Equally, modelers can computationally explore the mathematics of system paradigms presented as combinations of system archetypes by bridging them to stock and flow models. Every phenomenon and causal relationship asserted in a CLD should be bridgeable to a substructure arrangement of stocks, flows, constants, and auxiliaries and vice versa. Level of aggregation and method selection is an intentional step of selection to fit problem, purpose, and audience of a modeling effort.

### *5.4 Use of Metaphor and Analogy to Advance the Field and its Education.*

Another principle embedded in our approach is using metaphor and analogy to approach the reconciled order. Our use of these was deliberate. Long before complex systems were modeled explicitly in any fields, humans created natural language concepts to reconcile our mental models with the complex phenomena we observed around us. A metaphor is a symbolic connection accessing the reader's mental model to introduce a complex system they may be less familiar with by linking it to one they with which they have more familiarity. This use of metaphors as symbolic short hand for more complex representations has a strong history in several fields[30], [31] as well as system dynamics[10]. Analogies are a comparison between two things, often in terms of education. Again, the connection of an analogy relies on the reader's mental model knowing at least one of the two elements in the analogy. As metaphors and analogies are models, we recognize that all models are wrong, but some may be useful[28].

As a recent scientific field, system dynamics has few metaphors and analogies to aid new arrivals, be they students or stakeholders, in understanding what we do and how it works. Even as recently as the last ten years, as part of the authors' own journey through PhD efforts, we learned most of our practice of system dynamics as if assembling a jigsaw puzzle with a missing box, via finding individual pieces, and seeing how they fit together. The image on a puzzle box does not eliminate the validity of learning to piece together knowledge, but it does help frame where one is heading. Only recently have practitioners attempted systemic efforts to create such a picture of codified bodies of knowledge in either quantitative system dynamics modelers or qualitative systems thinking CLDs[32].

Additionally, metaphors and analogies are a useful basis for reconciliation. When two towns separated by a valley compare each other, the differences are manifest. However, a metaphor serves as a bridge, allowing each town to compare itself to a third thing, and in finding similarities they hold in common to that third thing, realizing the similarities they have with each other.

### *5.5 Limits to Growth of Requirements for Modeling*

A final principle we wish to discuss is what we hope this reconciliation does not do. In any professional field, a constant danger is the proliferation of tools that add complexity and burden to undertake any act in that field. We do not propose any of these principles as strict confidence-building measures, though as mentioned above they are useful for that. Nonetheless, superfluously demonstrating deconstruction and subsummation, scalar indifference, or bridging between mental and mathematical equations could add cumbersome and unnecessary work. When a specific confidence building challenge arises, for example the question of whether a phenomena in a CLD is a stock or a flow, if necessary, then modelers can and should apply these principles just like they would choose any other confidence measure based on the fitness of purpose and not a checklist of compliance. Instead, it is a feature of the versatility and rigor of our proposed reconciled order that such can be accomplished, if desired. It also creates pathways for connecting works created in one method to efforts in another.

## 6 Conclusion

In this note, we hope to contribute to a continued dialogue of reconciliation in the field by addressing tensions between quantitative system dynamics models and qualitative systems thinking CLDs. We showed how both rest on a common set of defining characteristics with one variation: whether they used mathematical or mental equations as the computation mechanism, and that both methods contained within them an order of constituent parts. We used a metaphor of a stonemasonry bridge and an analogy of the hierarchy of matter to arrange these constituent parts in four levels of combined a single reconciled order.

The resulting complete order, we hope, is fully encompassing the major constituent parts found in both methods.

The proposed reconciled order highlights the common first principles that accentuate the strength of these two methods in combination. That is the ability to decompose or subsume levels of hierarchy, a scalar indifference of the method to the problem, the ability to bridge between methods in terms of audience and greatest accessibility to understand the findings on a complex system.

Our purpose in suggesting this reconciliation goes beyond resolving tensions and finding a good order of things. We hope to make the field itself more accessible to students and stakeholders approaching it for the first time, with a basis of first principles and a picture on the box of a puzzle they are about to be asked to put together. Metaphors and analogies are useful both in education and reconciliation by accessing mental models in plain language to show how things initially perceived to be unalike can be found to have more in common when they both share traits with a third item.

We hope our proposed reconciled order for quantitative system dynamics models and qualitative systems thinking CLDs is not controversial. Experienced modelers already work between the two.
In practice, different schools of thought[2] may prefer one aspect of the order over another, based on the problems they seek to model. Nevertheless, just as different schools were never presented as a prison to confine individual modelers, the reconciled order is intended to be a bridge of connection rather than a wall of division. The metaphor of the bridge and analogy to the hierarchy of matter isn't to create further division, but make connections and interoperability between parts explicit by aligning them on first principles.

Bridging this divide encourages the two towns to interact more, traveling back and forth across the valley of complex systems that define their local geography. We presented the metaphor of the bridge and analogy to the hierarchy of matter not as strictly accurate, but to facilitate introduction, context, and understanding of the parts of the reconciled order and their operation within each level and across levels.

We seek and welcome the feedback of the field and members of the System Dynamics Society in continued discussion of reconciliation and rigor.

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