Disciplinarily-Integrated Games: A Generalizable Genre?

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Abstract: Disciplinary integration can be thought of in terms of Collins and colleagues' analyses of model types (epistemic forms) and modeling strategies (epistemic games). More specifically, the puzzles and game-play mechanics of disciplinarily-integrated games distill modeling strategies for navigating and manipulating model types. Framing disciplinary integration in terms of model types and modeling strategies opens a vast trove of epistemic forms and epistemic games that span across disciplines (in fact well beyond STEM into the social sciences). To explore the generalizability of disciplinary integration to games, the following sections propose other hypothetical examples in physics, biology, chemistry, and the social sciences. We discuss this generalizability in terms of its economic, curricular, and developmental implications.

Introduction

Clark, Sengupta, Brady, Martinez-Garza, and Killingsworth (2015) outline an approach for leveraging digital games as a medium to support the development of scientific modeling in K-12 classrooms based on the Science as Practice perspective (Pickering, 1995; Lehrer & Schauble, 2006). Clark et al. name this approach disciplinary integration and outline its development though a program of iterative research on student learning. Sengupta and Clark (submitted) extend the theoretical framing of disciplinarily-integrated games in terms of materiality within the classroom and the iterative design of multiple complementary symbolic inscriptional systems.

Clark et al. (2015) and Sengupta and Clark (submitted) propose that disciplinarily-integrated games represent a highly generalizable genre. To explore this claim of generalizability, the current chapter proposes other hypothetical examples of disciplinarily-integrated games (which we will refer to as DIGs for brevity) in physics, biology, chemistry, and the social sciences. We explore DIGs in three categories, beginning with model types and modeling strategies involving the nearest and simplest transfer of the DIG template and extending to those involving the furthest and most complex transfer: (a) time-series analyses with Cartesian formal representations, (b) constraint-system analyses with Cartesian formal representations, and (c) other model types and non-Cartesian formal representations. We close with the discussion of the implications of this generalizability.

Background

As proposed in Clark, Sengupta, Brady, Martinez-Garza, and Killingsworth (2015), disciplinary integration can be thought of in terms of Allan Collins's and colleagues' analyses of "model types" and "modeling strategies" (Collins, White, & Fadel, in preparation), which Collins and colleagues have termed "epistemic forms" and "epistemic games" in earlier work (Collins, 2011; Collins & Ferguson, 1993; Morrison & Collins, 1995). Collins and colleagues argue that the professional work of scientists can be understood in terms of model types (epistemic forms) that are the target structures guiding scientific inquiry and modeling strategies (epistemic games) that are the sets of rules and strategies for creating, manipulating, and refining those model types. While Collins and colleagues did not write with the intention of informing the design of actual digital games (they used the term "game" as a metaphor), DIGs can leverage the ideas of Collins and colleagues by structuring digital game play around modeling strategies (epistemic games) of designing and manipulating formal disciplinary model types (epistemic forms). More specifically, the puzzles and game-play mechanics of DIGs distill model types and the modeling strategies for navigating and manipulating those models.

As discussed in Clark, Sengupta, Brady, Martinez-Garza, and Killingsworth (2015), this specific emphasis on modeling as game play around disciplinary model types stands in contrast to engaging in "inquiry" more broadly, as is common in 3D virtual worlds (e.g., *Quest Atlantis*, *River City*, or *Crystal Island*). A key distinction between these two forms of virtual environments involves the nature and breadth of focus of the inquiry undertaken by students. Virtual inquiry worlds generally engage students in the practices and discourses (Gee, 1990) of a discipline at the level of inquiry writ large. Much of the pedagogical power and engagement of 3D virtual inquiry worlds tends to focus heavily on their impressive affordances for roleplaying, narrative, and identity-building (cf. Gee, 2007; Squire, 2011). As Clark, Sengupta, Brady, Martinez-Garza, and Killingsworth explain, however, while 3D virtual inquiry worlds are compelling and powerful, their scope and structure involve tradeoffs in terms of the individual tasks or puzzles. More specifically, individual tasks and puzzles are often relatively mundane (e.g., click on a character to be told a piece of evidence, click on a location to get a reading on oxygen levels, or click on a location to bring up another mini-game to collect evidence). Essentially, whereas 3D virtual inquiry worlds tend to cast students as scientists investigating a "mystery" at the level of overarching inquiry, DIGs do not attempt the depth of immersion, identity-building, and role-playing of virtual inquiry worlds (nor do we dispute their importance or value in virtual inquriy worlds). Instead, however, DIGs are designed to engage students more deeply in specific modeling and representational practices of developing, interpreting, manipulating, and translating across specific model types. This focus allows DIGs to progressively deepen the puzzle at the heart of the game and, more broadly, allows all elements of the game to emphasize that puzzle.

SURGE Symbolic

SURGE Symbolic is an example of a disciplinarily integrated game (http://www.surgeuniverse.com). Whereas earlier versions of SURGE focused on layering formal representations over informal representations, *SURGE Symbolic* inverts this order, layering informal representations over formal representations while organizing gameplay explicitly around navigating and coordinating across representations. Furthermore, while earlier versions supported reflection on the results of game play through formal representations as a means to support strategy-refinement, the formal representations were not the medium through which players planned, implemented, and manipulated their game strategies. The position graph, for example, can present information about the specific regions of the game-world that will be affected by dangerous electrical storms at given times, as well as about locations where rewards or allies will appear to rendezvous with Surge. As a result of this design approach, the Cartesian space emerges as a set of scientific instruments for the player, in the sense of providing access to data about the game world that are not available through other means. At the same time, the Cartesian graphs also play the role of an instrument panel or mission planner, offering fine-grained control over the movement of the Surge spacecraft.

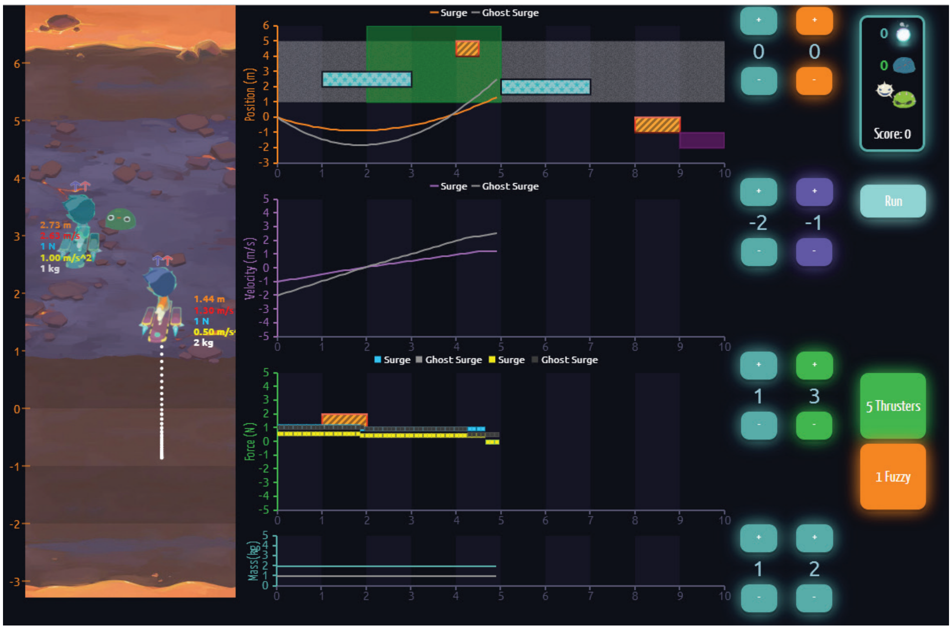

Figure 1: SURGE Symbolic

To date, we have primarily discussed DIGs in terms of *SURGE Symbolic*. To have value, the proposed template and genre must be generalizable. As discussed, disciplinary integration can be thought of in terms of Collins and colleagues' analyses of model types (epistemic forms) and modeling strategies (epistemic games). More specifically, the puzzles and game-play mechanics of disciplinarily-integrated games distill modeling strategies for navigating and manipulating model types. To explore this claim of generalizability, the following sections propose other hypothetical examples of DIGs in physics, biology, chemistry, and the social sciences. We will explore DIGs in three categories, beginning with the category involving the nearest and simplest transfer of the DIG template to the category involving the furthest and most complex transfer: (a) time-series analyses with Cartesian formal representations, (b) constraint-system analyses with Cartesian formal representations, and (c) other epistemic forms and non-Cartesian formal representations.

Time Series Analyses with Cartesian Representations

The nearest transfer of the template is to other topics focusing on time-series analyses where Cartesian graphs of change over time remain the focal formal representation. In such cases, the template outlined in this paper transfer relatively directly and require minimal discussion because the template remains essentially identical with time series analyses as the modeling strategy and Cartesian representations of change over time as the model type.

One example would involve exploring predator-prey relationships in population ecology. The time-series analysis of the populations could focus on the formal representation of population versus time, which depict the classic Lotka-Volterra equation relationships. Perhaps the phenomenological representation depicts the predator and prey animals within a given area running around reproducing, eating, and being eaten. The phenomenological and formal representations could be bridged by an intermediate representation that aggregates or stacks the animals in the phenomenological representation to clarify population levels. In terms of narrative, perhaps the player is an alien zoo keeper who needs to manage populations within the zoo. Perhaps the keeper can adjust temperature and irrigation in the zoo. As per the DIG template, the challenges and opportunities in a game level are depicted within the formal representation itself, perhaps as target levels for various populations at various times to avoid or attain. Also in line with the DIG template, the player specifies her strategy for an attempt in another formal representation, perhaps temperature and irrigation levels over-time, which impact plant growth and activity levels of predator and prey.

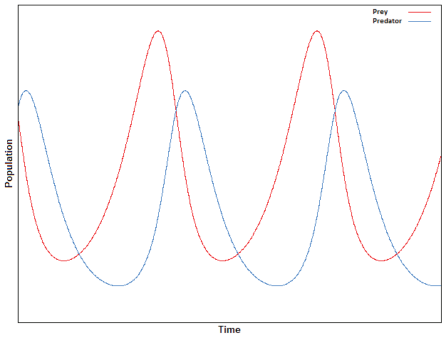

Figure 2: Cartesian graph of Lotka-Volterra equation.

In terms of other possible topics, the phenomenological view in a DIG for teaching chemical reaction kinetics might be a cylinder with various reactant molecules mixing together to create products. In terms of narrative, the learner might need to get a certain number of products by a certain time because the cylinder is being used to create a series of pills to help cure a disease. A DIG about the action potential might include a phenomenological representation that is a dynamic visualizations showing how sodium and potassium ions flow into and out of the neuron at the axon hillock. In terms of narrative, the learner might need to generate the specific membrane potential over time graph in question because he is trying to remotely control an alien organism he has engineered and set loose on a foreign planet. In designing a DIG to teach about glacial retreat the phenomenological world view would consist of a dynamic glacial tongue protruding from an artic land mass towards the ocean. For narrative, perhaps in order to transport a family of penguins along the glacier so they can meet their friends, the glacier needs to hit these target points to unite the penguins with their friends along the land mass. All of these proposed DIGs focus on Time Series Analyses with Cartesian formal representations, and thus all would use a very similar design template to the *SURGE Symbolic*. Essentially, the challenges and opportunities are presented to the player in the formal representations and the learner manipulates and creates her strategy and actions through the formal representations.

Constraint-Systems with Cartesian Representations

What about generalizing beyond Cartesian time-series analyses? Collins and colleagues outline a wealth of model types and modeling strategies in terms of structural, functional/causal, and process/behavioral analyses. We propose that the next most proximal category of DIGs focuses on the constraint-systems that include Cartesian representations with axes other than time. Collins and colleagues define constraint-systems as process/behavioral analyses where: (a) the model type is the equation (or equations) describing the steady state of the system and (b) the most common modeling strategy is the controlling variables game where one variable is manipulated at a time while all others are held constant to determine its behavior on the system. Constraint-system analyses there lend themselves to displaying relationships using Cartesian graphs as the formal representation with one variable along each axis and the other variables as controls for manipulating the Cartesian graph.

In the domain of chemistry, the ideal gas is one possible example of a constraint-system analysis DIG. The ideal gas law is governed by the equation PV = nRT, where notably “P” stands for pressure, “V” stands for volume and “T” stands for temperature. Here, the phenomenological view would be a simulation game environment where molecules move around in a container and the learner can make the container larger or smaller (volume) by adding or removing blocks to compress of enlarge its lid and increase or decrease the temperature by altering the size of a flame on the system. Pressure is a byproduct of an increase in kinetic energy of molecules, temperature, and thus cannot be altered directly. Pressure in this system is visualized by a series of red marks on that occur every time a gas molecule collides with the container. There are numeric readouts for all three of these variables in the simulation. Here the learner can hold one of these three variables constant by clicking on a button designated for each, and can manipulate the other two variables, one variable at a time to see the effect they have on each other. For example, the learner may hold the pressure variable constant in this system, and then compress/enlarge the lid of the container to increase and decrease the volume and see the effect this has on the temperature in the system. In this game, the learner has to generate a certain amount of gas pressure in a container that will be transferred to specialized cells needed to power a hovercraft he uses to explore an alien world. If the cells have too much gas pressure they will burst, and if they have too little, they won’t have enough to power the craft. The learner sees a Pressure vs. Volume graph with a target box at the proper amount of pressure. The learner alters the flame level to change the temperature in the system and then adds or subtracts blocks on the lid to alter the volume of the container holding the gas. As he does this, he sees the Pressure vs. Volume graph being created and can see if the target box is hit or not, thereby winning the level or losing it. The target box could be placed instead on the Volume vs. Temperature graph in a different level, where the learner has to generate a particular volume in the gas in order to transfer it to cells used for a different purpose in the hovercraft.

In the domain of physics, our DIG framework could be applied to the constraint-system of Coulomb’s force or repulsion and attraction. This system is particularly interesting for Cartesian graphs because it involves both multiplicative and exponential relationships (F = k * q1 * q2/r2). Here, the phenomenological view would be a series of charge spheres, where the learner could control the distance between the spheres (r) and the charges on each sphere (q1, q2). The narrative might cast the learner as a space explorer on a space ship who needs to achieve the right amount of repulsion or attraction between charge spheres in an alien device in order to get it to work and see what it does (parallel to game-play in *SuperCharged*, Squire et al, 2004, but played out in the formal representations rather than in a simulated world). All of these constraint-stem analyses parallel the time-series analyses examples in using a Cartesian graph as the formal representation that presents the challenges and opportunities in a game level as well as a Cartesian graph or graphs through which the player plans, authors, and executes her strategy for the game level.

Other Epistemic Forms and Non-Cartesian Formal Representations

The previous sections suggest that the DIG template and genre proposed in this paper are generalizable to topics focusing on time-series analyses and constraint-system analyses where the formal representations are Cartesian graphs. This opens up a wide range topics across which the genre might apply. But what about other model types and modeling strategies beyond these?

Collins and colleagues (Collins & Ferguson, 1993; Collins, 2011; Collins et al., in preparation) discuss three different major groups of model types: “(a) structural models for analyzing the structure of phenomena, (b) causal and functional models for analyzing causal or functional aspects of phenomena, and (c) behavioral models for describing the dynamic behavior of phenomena” (Collins, personal communication). The time-series and constraint-system epistemic games we have focused on thus far in terms of possible DIGs are behavioral models (which Collins and Ferguson, 1993, originally termed “process analyses”). Process/behavioral models focus on the dynamic behavior of phenomena. The major behavioral/process model types discussed by Collins and colleagues include: system-dynamics models, aggregate-behavior models, constraint-system analyses, situation-action models, and trend and cyclical analysis (with time-series analyses being a subset of trend analyses). With that in mind, the next place to look for possible DIGs would be in this behavioral/process set of model types, which makes sense given that a focus on dynamic behavior lends itself well to the medium of digital games.

System-dynamics models, for example, seem promising for DIGs because they involve specifying relationships and action sequences that determine/predict outcomes given a scenario or set of parameters. In a system-dynamics model, variables are linked together by positive or negative links. Variables can be increased or decreased, which in turn changes other variables in the system though the links. These models can be qualitative or quantitative. Various lag, homeostatic, or feedback functions can be built into the models. Climate, economic, ecological models, and models in many other disciplines can be structured as system-dynamics models. The figures below present a simple system-dynamics models for economics and for population ecology.

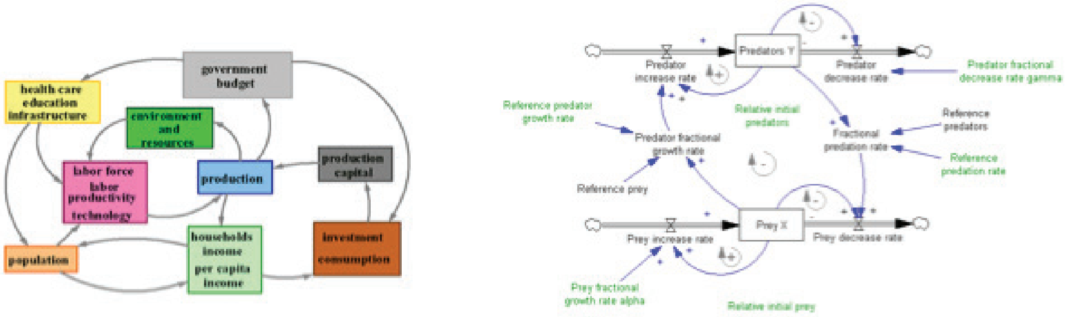

Figure 3: System-dynamics models for economics and population ecology.

Could interesting game-play be built around interpreting and manipulating a system-dynamics model? Actually, such a game has already been developed as a recreational "indie" franchise of games that has been highly successful commercially. *Democracy I, II,* and *III* are essentially system-dynamics models (http://www.positech.co.uk), where the changes you make to one variable influences all of the connected variables (either positively or negatively depending on the valence and magnitude of the link). *Democracy* is a great example because all of the game-play is centered and focused in the formal representations, which in the case of *Democracy* is incredibly complex with a huge number of nodes, but which would not need to be so complex for other games. Nonetheless, the *Democracy* example focuses entirely on reading and manipulating a single formal system-dynamics representation while monitoring other formal representations for information and changes across variables. Thus system-dynamics models, in conjunction with other formal representations, clearly are viable for DIGs. System dynamics models might also be implemented in DIGs as the control representation. In the earlier example about population dynamics, for example, rather than using Cartesian change-over-time graphs for the player to plan and author her strategy, she might manipulate the population system-dynamics model, above, to plan and author her strategy while a Cartesian graph of populations over time might still be employed as the representation that presents the challenges and opportunities for the level.

In terms of other process/behavioral model types, situation-action models are also promising for sciences as well as social sciences and robotics. Situation-action models specify a set of if/then rules that specify what actions an agent will take in what situations. As situations change, either because of previous actions or because of changes in agent's environment, the rules then specify the next actions (or inaction). Such situation-action model rule sets could be used either for player control or for game communication of challenges and opportunities in a level. In the population ecology game, for example, a situation-action model might be used for the player to author her strategy by specifying the actions and properties of the animals being modeled, which might then play out in a system-dynamic model or an agent-based model (another type of behavioral/process model).

While behavioral/process model types thus seem fertile ground for generalizing DIGs, Collins and colleagues' structural-analysis model types or causal/functional model types seem like more challenging terrain for DIGs. Structural-analysis model types "include compare and contrast, cost-benefit analysis, primitive elements analysis, tables or cross-product analysis, tree structures or hierarchical analysis, and axiom systems. Structural-analysis [model types] answer the question 'What is the nature of x?' by breaking x down into subsets or constituents and describing the relationships among the constituents" (Collins & Ferguson, 1993, p 29). Causal/functional analysis model types specify "the causal or functional structures that relate elements in a system… These include critical-event analysis, cause-and-effect analysis, problem-centered analysis, multicausal analysis, and form-and-function analysis" (Collins & Ferguson, 1993, p. 33). Structural-analysis and causal/functional analysis model types are less dynamic than process/behavioral analysis model types.

In DIGs, structural-analysis model types and causal/functional model types might support more static or less dynamic puzzle-like or mystery type of games where the player is working to construct or discover the relationships in the model. Structural-analysis model types and causal/functional model types might well however be incorporated into DIGs in tandem with other more dynamic models for more dynamic game-play. The model that articulates the challenge and goals for a DIG, for example, might be a dynamic agent-based model from which the player needs to deduce the relationships of the elements/agents within some structural-analysis or causal/functional model type. In this case, intermediate representations would likely be very helpful for payers in translating between the different formal representations. While these examples for suggest that the overarching genre of DIGs might indeed be generalizable for structural-analysis model types and causal/functional model types, however, the DIG genre outlined in this paper seem most generalizable across behavioral/process analysis model types.

Final Thoughts: Generalizability of Genre

We therefore propose that disciplinary integration of digital games provide a generalizable genre that holds promise as a vehicle for engaging students with key model types and modeling strategies that cross multiple disciplines and respond to calls for greater emphasis on problem-solving, 21st century skills, and engaging students in the practices of disciplines to develop deeper understanding. We now close the paper by considering the implications of this proposed generalizability in terms of the propagation of digital learning games across the curriculum and the conceptual development of students within this integrated curriculum.

Up to now, developing digital games for learning in multiple disciplines at an economically feasible budget has often devolved into simple forms of gamification (i.e., simply layering points and badges over mechanics that are not themselves game-like). Developing a game where core disciplinary ideas drive game-mechanics, on the other hand, has proven time-intensive and cost-intensive. This, in turn, has created a barrier to the systematic integration of digital games as a medium across the curriculum. A potential advantage of the generalizability of the DIG template proposed in this chapter is that once a DIG template is honed and refined through iterative cycles of design and research, then other games can be developed building on the conceptual, design, functional, and software foundations of that DIG template to create other DIGs in other disciplines that focus on the same epistemic forms and games. This could therefore create important economies of scale in terms of development time and cost.

Even more importantly, this generalizability has critical implications in terms of the development of students across the curriculum and integration across the curriculum. Much research on digital environments in the classroom focus at the level of the activity rather than the level of the longer-term curriculum because of the limitations of development of technology. However, the conceptualization of DIGs as multiple representational systems lends itself well to thinking about the connections between the curricula beyond DIGs in terms of the epistemic and representational forms therein, which we describe next.

The “science as practice” perspective is rooted in the long-term production of scientific knowledge through the long-term development of epistemic and representational practices. However, in a K12 science classroom, students typically have to learn several different domains during the same academic year, thereby minimizing opportunities of meaningful, long-term engagement within a single curricular unit. However, by considering the epistemic and representational forms within each unit, a few DIGs could be interspersed throughout the academic year with the goal to meaningfully connect across the preceding and succeeding curricular units. Within a DIG, the multiple representational systems can be designed in a manner that learners being with a familiar representational form, develop intermediate abstractions, and then generate new representational forms that are not only canonically more sophisticated, but can also provide become representational forms that are used in the succeeding curricular unit.

In its strongest form, therefore, DIGs can help us conceptualize the year-long science curriculum as a careful assembly of curricular units, arranged in terms of meaningful connections between epistemic and representational forms, help us design DIGs that can create a meaningful coherence across these units. From the perspective of student learning, it shifts the focus from thinking about learning within a game – i.e., a short-term focus on learning – to the development of epistemic and representational practices that are central to the long-term development of scientific expertise in an authentic manner, i.e., in a manner that is representative of the professional practice of scientists.

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