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MODELLING IN DESIGN-AND-MAKE: SYNTHESIS OF A BIOLOGICAL CELL INTO A BOARD-GAME

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Modelling is an integral part of the design-and-make experience. The translation and use of knowledge from one domain to develop a production in a different domain requires deeper engagement. This paper reports a pedagogic experiment involving social science undergraduates designing and making a board game for secondary schools students to help understand a biological (animal or plant) cell. Analysis of board games revealed two forms of engagement with modelling: abstractive and transformative. Models that captured the essential features generalisable of a typical cell into a different form of representation were identified as abstractive kind. Other cell models which extracted conceptual ideas and re-represented them into a distinctively different form, opening newer ways of imagining were classified as transformative. The study offers insights into how modelling enriches conceptual learning and exemplifies possibilities of integrating design-and-make in higher education.

DESIGN-AND-MAKE AS VALUED CONTEXT FOR LEARNING

The contemporary educational discourse aims at making school learning meaningful and engaging. The proposals for integrating design and technology (D&T) education within the ambit of school education are receiving greater reciprocation from diverse stakeholders. Design-and-make units have potentials to provide relatable contexts for inquiry and learning (Baynes, 2010; Kimbell & Stables, 2007). They provide opportunities for simultaneous immersion into knowing, doing, meaning-making and transcending knowledge across disciplinary boundaries (Khunyakari, 2019). Studies within the global (Banks & Barlex, 2014; Crismond & Adams, 2012) and the Indian context (Khunyakari, 2015) vouch for curricular and cognitive gains through an integration of design-and-make in school curricula. The learning processes involved align with naturalistic patterns of human learning rather than knowledge presented as piecemeal, isolated bodies of information. More importantly, design-and-make experiences have scope for developing creative ingenuity, empathy, critical reflection and social consciousness among individuals engaging with the learning activities.

Models and Modelling in D&T education

The process of modelling is an inseparable part of design and technology endeavours (Elmer 1999; Welch, 1998; Davies, 1996). Roberts, Archer & Baynes (1992) argue that modelling plays an equivalent role of language in the process of designing. Barlex (1991) hints at the role of model, different from physical artefact or end in itself, serving as an aid to reveal pupil's thinking. While acknowledging instrumentality of models, Liddament (1990) argues the need to distinguish use of models as 'information carriers' from those serving teaching function. Teaching, which involves supporting learners in identifying and elaborating the underlying conceptual structures, through modelling has been less researched. Smith (2001) proposes categorisation of models into three kinds, namely; *iconic* (representing a product or part of it, e.g. drawing or 3D model of kettle handle), *analogue* (diagrams using symbols to represent a system or product, e.g. electronic circuits) and *symbolic* (using abstract code to represent aspects of an existing or possible product or system, e.g. mathematical model of a bridge). Archer (in Roberts et. al., 1992, p.9) argues 'humans construe sense data and construct representations spatially and presentationally, rather than discursively and sequentially.' He asserts that 'cognitive modelling' is unique to designing, enabling one to form images in the mind's eye, and have capabilities to operate, manipulate and evaluate them.

RELEVANCE OF THE STUDY

The efforts directed towards understanding learning processes resulting from an assimilation of cross-cutting concepts are increasingly gaining recognition (NGSS, 2013). Several studies attempt to identify and underscore the connections across disciplines by inquiring into the nature of disciplinary knowledge brought to bear in a particular unit or activity. However, such a fact-finding exercise does not serve much beyond the purpose of validation. In such studies significant ideas related to practice, such as, the quality of connections made, the kind of support afforded, forms of assessment used, etc. do not become explicit. In other words, the qualitative nature of the conditions that afford learning remain hidden. For instance, the contexts that stimulate individuals to pursue a concept from across domains (of knowledge), either by morphing or radical transformation of seed ideas into meaningful outcomes in another domain (of use), are seldom investigated. Such experiences provide the necessary hooks to anchor possibilities for re-thinking about teaching. No matter how raw in their character, studies involving practice and 'pedagogic experiments' have the potential to offer valuable insights into the cognitive realm of human learning involving interactions with problem scenarios, knowledges, and collaborative action. Although experiences of D&T education for primary and secondary school students have been well documented, there are sparse reports of design-and-make at the higher education level, particularly in the Indian context. An increasing emphasis on subject specialisations and disciplinary streaming in higher education offer little opportunities for exercising the use of cross-cutting concepts. The pedagogic experiment reported in this paper invited social science undergraduates to venture around a central concept in life sciences (otherwise considered outside their domain space).

OBJECTIVES OF THE STUDY

Since the study involved teaching, the primary objective was to transact conceptual understanding of structure and functioning of biological cell and its internalisation in a meaningful way among social science undergraduates. The research objectives addressed are:

1. To investigate the worthiness of design-and-make experience for engaging social science undergraduates to think about fundamental concepts in the sciences.
2. To study the conditions and evidences structured around the design-and-make experience that provided opportunities for learning.
3. To critically examine students' work, their reflections and the resulting learning outcomes from being involved in the process.

THE STUDY

The study involved a ‘pedagogic experiment’ at the interface of teaching, development and reflective analysis. Social science undergraduates, after an exposure to foundational ideas around biological cell, were invited to collaboratively design-and-make a board-game that would help teach the concept of biological cell to secondary school students.

Participants

The participants were 60 students, enrolled in the B.A. in Social Sciences (BASS) programme at the University, where the author taught participants a 2-credit (30 hours of teaching), core course on Introduction to Life Sciences. The undergraduate programme had a mix of students from the arts, commerce and science streams. They represented diverse cultural and linguistic exposure, from across India. Usually participants in this programme come with a disinterest for the sciences and aim for a career in social development sector. Addressing the disinterest towards the sciences and seeking a relevance between the sciences and the social sciences in the first year of BASS poses challenges. The participants volunteered to work in 16 teams, each consisting of 3 to 4 individuals. Teams attempted to have a fair representation of genders, alignment interest in pursuing either an animal cell or a plant cell, and have at least one member who had studied biology at the higher secondary level. The criteria helped the teacher-researcher maintain some form of parity across teams. Individuals within each team engaged themselves in the task during break-time, after their class hours, and over weekends.

Nature of the engagement

The author, a teacher-researcher, has been teaching the course for the last 6 years. The data for this study is from the academic year 2017-18. The course aimed to develop an appreciation of fundamental ideas in life sciences that have contributed to the advancement of human knowledge and to the development of society. Going beyond just explaining the concepts, the pedagogic effort was to help students locate ideas within their historical contexts, relate to the processes involved in the discovery of scientific insights, and develop an understanding of the nature of socio-cultural and political influences shaping scientific endeavours. The breadth of ideas that can be potentially covered through such a course plan is exhaustive. Hence, the effort during course teaching was to revisit some salient ideas that not just brought a transformative character to the erstwhile knowledge but also reformed the approach to human thinking and understanding. For instance, uncovering structural foundations of life, biomolecules in complex functional existence, processes of transmission of characters (basic genetics) and change over generations (evolution). Through the process of revisiting ideas, course participants were encouraged to find relevance of ideas in contemporary contexts.

Process of the engagement

The design-and-make engagement was contingent on two kinds of ‘knowing’: (a) knowledge of the diverse board-games which can help trigger ideas and (b) foundations of structure and functioning of a biological cell. The participants were encouraged to use readily available resources, if possible, re-using waste materials in their immediate environment. As an initiation, a few visuals of board-games from different socio-historical and cultural contexts were shared. A trailer clip of the movie ‘*Jumanji*’ added an element of fun and excitement. In the examples showcased, attention was drawn to features such as variety of materials, design elements like props, end-goal and norms of playing. The design-and-make task was situated within class discussions on the emergence of cell concept, formulation of cell theory as an explanation to structural organisation and procreation. Understanding biological cells invited participants to learn about organelle components, their structures, functional mechanisms, and develop knowledge about similarities and differences of a typical animal and plant cell. This content is very much a part of school science, but without the inclusion of history and social conditions that shaped the discovery of biological cells. Very often the school science projects demand learners (with support from adults) to make physical, 3D models of animal or plant cells with materials such as styrofoam. Such physical modelling is limited to a mere translation of information from standardised 2D, diagrammatic representation into a 3D, static, projective depiction. Such an act of reproduction, conceived as ‘modelling’, is celebrated as an outcome of knowledge about organelles and processes of a biological cell. In this study, modelling is understood differently. The designing and making of a board-game was not just a means to build and assess their understanding of concepts and skills but also a means to invoke and relate to their ‘conceptual models’. The research followed the development of design ideas and realisation of board-games, on lines of a pedagogic structure of collaboration & communication centred D&T education, described in Khunyakari (2015). The outcome of this learning activity went far beyond communicative elaboration to serving a means for generating interest, enthusiasm and knowing intricate details about biological cells. While the end-products gave insights into students’ understanding, the process of engagement opened up avenues to capture cognitive aspects of learning within collaborative environments, internalisation of concepts and their application into a different context.

Forms of data

The primary sources included portfolios maintained by each team, a write-up that included instructional manual for playing, and the production (board-game) itself. Team portfolios included sketches, drawings, raw ideas, information and details about biological cells, and worksheets. Following the data closely allowed noting transitions and evolution of ideas through the phases of design-and-make.

ANALYSIS AND FINDINGS

This findings are organised in two parts. A discussion on generic observations hints to conditions and evidences that triggered and supported learning. Elaborate description of two cases allows nuanced appreciation of learning.

(A) Generic observations

Out of the 16 teams, 11 teams chose to work on designing a board game around an animal cell while 5 teams worked on plant cell. The coinage of names indicated a metaphorical or an analogical connect. For instance, *Battle-via-cellula* (Understanding battles through/in cell), *Celluzzle* (The puzzle about cells), *Fort-o-chondria* (The granular castle). Translating knowledge of biological cells into board games required a command over concepts. The interests and exposure to scientific knowledge within each team varied. Often, the teams made copious notes about cell organelles, their structure and functioning. The collaborative nature of work allowed for an intermingling of concepts and skills. Collaborative discussions involved identifying symbolic salience of organelle functions and abstracting how this could be used during planning. Teams planned ‘making’ using sketches, texts and materials from their immediate environment. The participants personalised their board game as a ‘work of art’, translated ideas into material forms, calculated area and developed rubric for scoring the difficulty levels. Analysis of portfolios revealed prudent judgement by participants in tailored use of text for specific purposes like collating information, brainstorming ideas, planning changes, reflecting and reporting. Selective transformation or adaptation of known elements was driven by the following considerations: entry or exit points; envisaging the goal, levels of engagement and challenges in the game; sustaining more than two players; and scoring (goal-achieving) scheme. Teams consciously selected affordable and easily available materials such as sand, cardboard, erasers, nail paint, broken marble pieces, cloth, etc. They developed manuals for detailing rules, introducing components and props/pawns. Portable designs which could fold and fit in small spaces indicated explicit attention to ergonomics. Often the features of props, such as colours, shape and materials, aligned with the organelle features and their functions. Although board games have an implied necessity of a ‘board’, the ingenuity of participants reflected in varied use of cloth, cardboard and chart paper. The making involved a careful synthesis of details and decision-making. For instance, how many players can be involved in a game at a given point, how many flashcards need to be created and what could it contain, scheme for reward points, etc. The findings suggest fluid integration of knowledge and skills from across disciplines. Simultaneous and explicit attention to conceptual content, aesthetics and packaging reflected deep involvement and continual strive for quality outcome.

(B) Learning from two cases

Each case description includes inspirational ideas, articulated objective/s, and target audience. Aspects of manufacturing (material and resource considerations), rules, notations, and scoring rubrics developed form the second part. The last part has reflections on students’ work, observations about productions, and pointers that unfold cognitive aspects of engagement. A representation of plant and animal cell was deliberate, but the choice of cases was random.

Case 1: Cell Castle by Team *Trifolium* [Team 4]

Designed for children aged 12 years and above, this team worked on a board game plant cell to meet the dual purpose of education and enjoyment. The decisions to include a typical plant cell diagram and basic information on flash cards was rationalized as being age appropriate. The team drew inspiration from games like Snake & Ladders, Monopoly and Guess Who.

Unlike the other board games developed, which used either a chart paper or a cardboard sheet for making the primary surface, this team painted a typical plant cell on a white cloth (see Figure 1). The game had a maximum of 4 players, represented as 4 distinctly coloured pawns, stationed at four different places outside the cell and exhibited a colour correspondence. The board game was about taking each player through a journey of information about the various plant cell organelles. A roll of dice resulting in a score of either 2 or 5, entitled the player to pass through cell wall and cell membrane, pick Card 1, and occupy the “START” position. The player then passed the dice to the next player. No player gets an extra turn, either on getting the suitable position or even if the player gets lucky with 6 number upon rolling the dice. The player needs to wait for her/his turn and follow instructions provided on the card. Each flash card bore a number. The number co-ordinated cards had information about organelles and instructions that enabled a player to move forward in the game along the pre-determined path. The path of movement, identified as blocks, spanned the cell environment and also passed through organelles. Appropriate flash cards needed to be read aloud on reaching an organelle block. The game included suitable incentives and punishments (in the form of danger blocks that pull you back, painted red). The player succeeding in assimilating maximum information about cell organelles compared to her/his peers emerged as the winner.

Value considerations seem to shape designers' decisions, from the early stages of planning. The decision of providing information about organelle and its functioning through flash cards achieves the purpose of strengthening knowledge as well as retaining the fun component. Non-intrinsic (extraneous) values such as making the board game portable, cost-efficient, and environment-friendly influenced design of this product. In highlighting an interplay of knowledge and values in technological learning engagement, Pavlova (2005) emphasizes the need to be conscious of intrinsic and non-intrinsic values that shape design decisions. Further, Khunyakari (2019) argues that values considerations may take the role of primary generators during the process of designing. For instance, the self-imposed constraint of cost-efficiency translated into the need to reconfigure broken pieces of marbles into pawns by employing creative, aesthetic skills. Team's board game harnessed modelling to achieve representational access to abstract concept along with strengthened association and reinforcement of relevant information. Such a form of modelling that goes beyond just using a different medium for representation and focuses on extracting salient attributes, enriching information and aiding visuo-spatial thinking has been referred to as "abstractive modelling".

Case 2: *Étude Sur La Vie* (Study about Life) by Team MAD Creations Ltd. [Team 7].
A set of neatly packaged items in a box constituted the board game. The contents included a rectangular board folded along its long edge, a user manual, a guidebook for game-keeper, three sets of flash cards, box containing cell organelles, and a small box with dices and pawns (see Figure 2). The board game involving 2 to 4 players and a game-keeper, designed to unfold in three levels, aimed to assess understanding about animal cell among children aged 13 years and above. Team drew its inspiration from the games as Candyland and Bookchase.

Figure 1: Board Game of Team *Trifolium* **Figure 2:** Board Game of Team *MAD*

The game had three levels. Level 1 invited players to roll the dice to get an appropriate score for choosing a card. Answering correctly the question on the card would establish a claim to cytoplasm (represented as circular structures covered by fine sand). A correct response would yield the packet of cell organelles, which the player needed to place on the cytoplasm in order to complete the model of animal cell. For each of the cell organelles, the game keeper would raise questions. The completion of this level takes the player to the next level. In Level 2, the player needs to roll the dice to a number to secure a molecule. The player in the next turn needs to get the right number on dice to choose the specific transport mechanism for their organelle. Since organelles have specific transport systems, getting a correct transport system is critical to the movement of the molecule across the semi-permeable membranes. If the player succeeds in achieving the right number, corresponding to the system, the pawn makes an entry to the cell system, taking the player to the last level. In Level 3, the player needs to pick up cards, one at a time. These cards contain instructions and some (negative or positive) points. For instance, a waste material card yields some negative points whereas cue card for vacuole allows the player to eliminate all waste material cards to vacuole since vacuoles in animal cells store wastes. As a result, the player would now have only positive points. The player with maximum score, among the four, would be the winner. Gradual progression across levels beginning with developing an understanding of cell components through a piecemeal assemblage in Level 1 to internalising the mechanism of transport for molecules in Level 2 to associating an understanding of form and function in Level 3, retains the dual purpose of sustaining interests and building levels of knowledge. The considerations of material cost and expenditure in making, remained with the team from the initial design until the production stage. A judicious choice of local materials, such as, papermash, clay, etc. and re-use of resources as “Old Amazon Box”, Pasta box, etc. while estimating budget and during making is suggestive of economic consideration in play design. Students’ ingenuity got expressed at various stages. For instance, in choosing a latin name for their board game to deriving the acronym ‘MAD’ from first letters of their names. Further, the game architecture used materials that capture organelle characteristics, colour coded scheme, and scoring rubric that symbolised aspects of organelle functioning. For instance, in Level 3, if a player gets a lysosome in her/his card, s/he must keep her/his pawn outside the cell and go back to Level 2. Participants’ conscious use of rules aligned with conceptual understanding of processes in animal cell functioning. Such an extension of knowledge to model the movement of a biomolecule across organelles within cell is an exemplification of transfer of knowledge. Haskell (2000) argues the need for creating opportunities that necessitate transfer of learning by recognising and extending opportunities of engagement to novel contexts and situations.

The norms set for fair play are critical to any board game. Analysis of these reveal the degree to which human actions were anticipated. Hence, rules of game and the scoring scheme together provided the framework for optimising cognitive engagement during play activities. For instance, an anticipation of a limited number of cards as cues made participants frame two constraints as rules. The first constraint was to read the cue card quietly and not share it with the other player. They could, however, talk aloud the answers. The time limit of two minutes per question served as the second constraint. Both constraints demanded a continual, focused engagement of players. Serious attention to details was noted not just in designing the product, but also in its packaging. Symbols for handling, the bar code and the label of manufacturing, all brought a professional character to the finished product. The team’s use of modelling to gain a focus on conceptual ideas by re-representing existing understanding into distinctively different forms thereby opening scope for questioning and challenging ideas and initiating search for deeper knowledge has been referred to as "transformative modelling". Through modelling, this team attempted to surpass the goal of strengthening or associating information to creatively recasting the content in a manner that renews or alters possibilities of thought, invoking a deeper knowledge of cell.

CONCLUSIONS AND THE WAY FORWARD

The pedagogic experiment invited social sciences undergraduates to collaboratively design a board game as a means to revisit cell concept and develop context for extending understanding. In conventional teaching, knowledge about cells is packed as information. Designing a board game presented participants with an opportunity to 'model' understanding and balance learning with fun. Participants' engagement with design-and-make of board games, without an orientation or exposure to principles of creating board games, elicited two kinds of modelling, which have been referred to as abstractive and transformative modelling. Case 1 exemplifies abstractive modelling where the team seemed to have used modelling for representational access along with reinforcing the relevant information. On the other hand, Case 2 represented transformative modelling, where the team's effort was on re-representation into an altered form that explored conceptual ideas and affording scope for operating on knowledge and refining it further. Analysis of the varied associations related to the processes of modelling in the context of this study also hints to a complex interplay of intent and knowledge, which needs to be pursued further. The context of play allowed exploration of a variety of board games, some of which have deep-seated, cultural histories. Although the dimension of culture has not been focused in this study, the data suggest the role of cultural exposure as an influence on design development. Tapping the experience for uncovering alternative conceptions related to understanding cells and mental models that participants operate upon would be an interesting dimension of inquiry that can be pursued further.

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